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GIS Analysis of the Caves and Karst of the Mariana Islands

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GIS ANALYSIS OF CAVES AND KARST OF

THE MARIANA ISLANDS

By

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GIS ANALYSIS OF CAVES AND KARST OF THE MARIANA ISLANDS

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The Mariana Islands are a volcanic island chain in the western Pacific Ocean composed of Eocene volcanic cores with a carbonate mantle. Others have classified the cave and karst features into the cave types described in the CIKM, but no comprehensive GIS has been developed. For this project, a comprehensive GIS of the cave and karst features was developed. The cave and karst features were divided by cave type, physiographic province, and island. The karst features in the GIS were hyperlinked to a series of HTML pages, one for each island, and a set of HTML navigation pages mirroring the GIS layers were also created. LANDSAT images and Digital Raster Graphics were draped over the Digital Elevation Models for visualization. Attempts were made to remotely sense the vegetation and exposed soils and rocks from the LANDSAT images with the goal of producing a theoretical subsurface limestone/volcanic contact. Although the overall remote sensing aspect was unsuccessful, the GIS inventory was a success.

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CHAPTER I

INTRODUCTION

The purpose of this thesis is to develop a comprehensive GIS database of the caves and karst of the Mariana Islands and to perform GIS analyses on the data in order to identify patterns in their development for the purpose of land use management, and fresh water resource management for the islands. There has been much work in inventorying the caves and karst features on the Mariana Islands, but there is not yet a comprehensive GIS database of the cave and karst features. In addition, no analysis has been performed on the cave and karst features in the existing, but disparate, GIS databases.

CHAPTER II

THE MARIANA ISLANDS

Geographic Setting

The Mariana Islands are an island archipelago located south of Japan (Figure 1) in the western Pacific Ocean where the Pacific Plate is being subducted beneath the Philippine Plate, to the west of the Mariana Trench. It is this convergent plate boundary that is responsible for the formation of both the Mariana Trench and the Mariana Islands. The Mariana Islands are composed of fourteen islands divided into two parallel island chains that are the subaerially exposed portion of the Mariana Ridge (Figure 2) (Karig, 1971). The western volcanically-active chain is composed completely of volcanics and is not included in this study.

Because many Chomorro words begin with prefixies that are also English words (e.g. *As*, and *I*) all Chomorro words and place names in this document are in *italics* to reduce reader confusion. This follows the convention from Keel (2005).

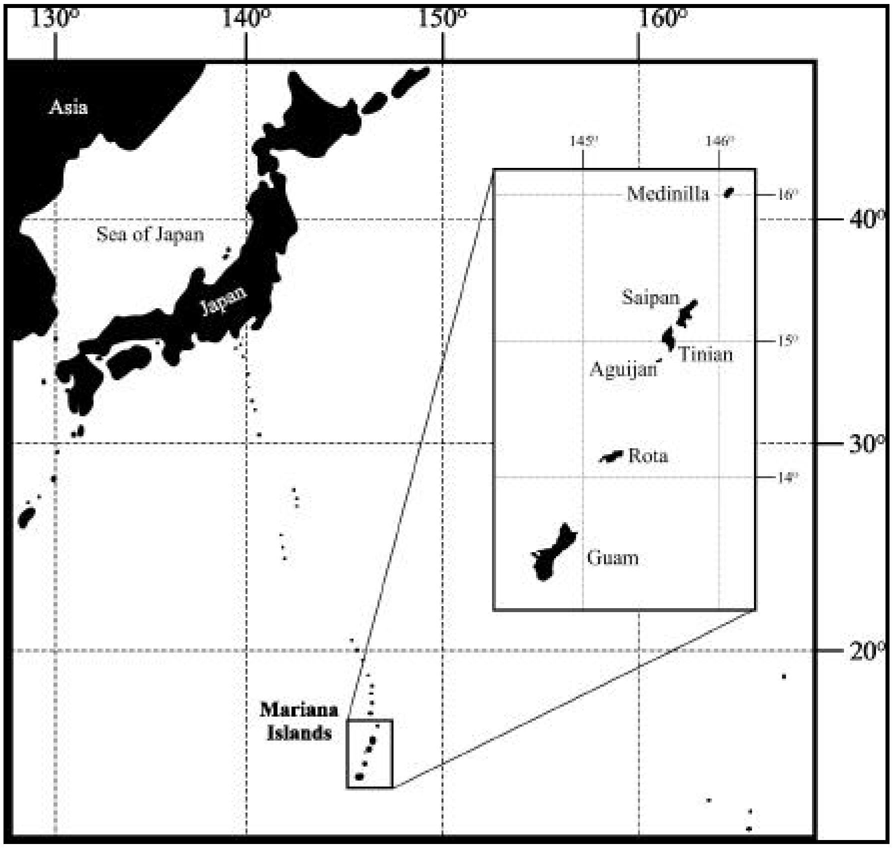


Figure 1: Location map of the Mariana Islands (Jenson et al., in press)

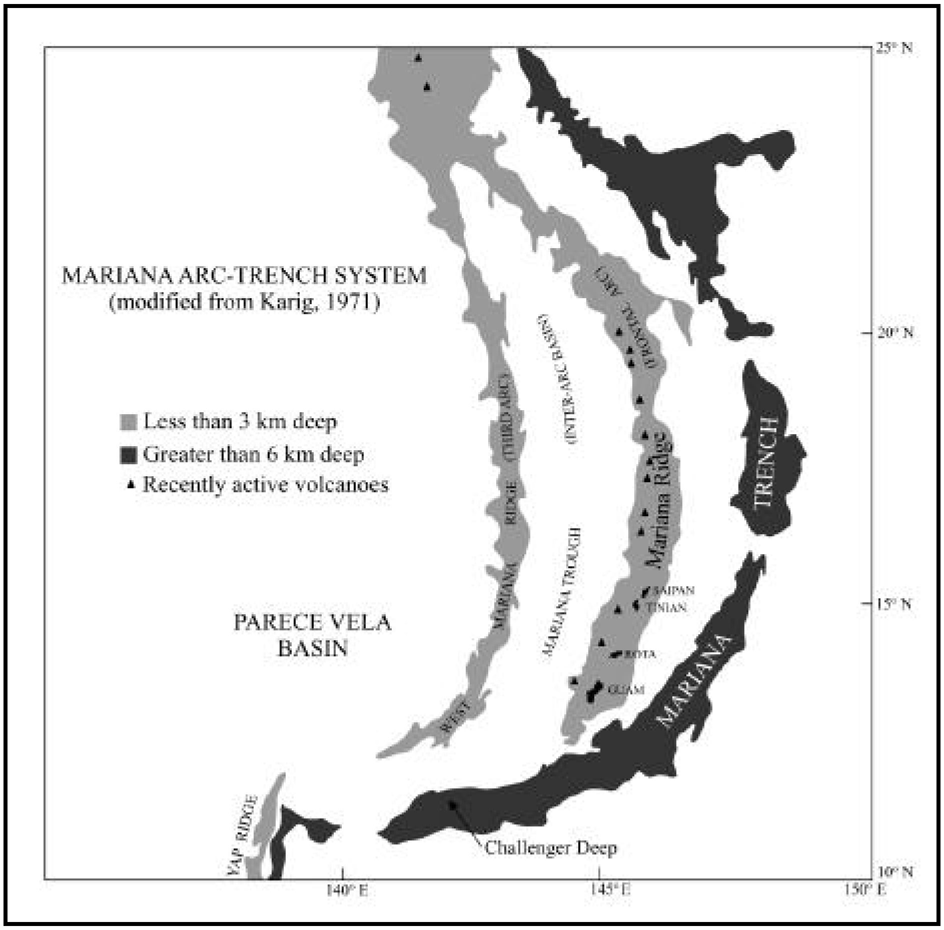


Figure 2: Mariana Arc-Trench System (Keel, 2005)

All of the islands in the eastern chain of the archipelago are composed of a paleo-volcanic basement with a cover of Cenozoic carbonates. There are six islands in the eastern chain of the Marianas (Guam, Rota, Tinian, Saipan, Aguijan and Farallon de Medinilla). The chain continues north of Farallon de Medinilla as a series of sea mounts (Karig, 1971; Cloud et al., 1956). The Marianas are made of two separate political entities: Guam is a Commonwealth of the United States, and the remainder of the islands in the study are in the Commonwealth of the Northern Mariana Islands.

Guam, the southern-most island in the western chain, is located about 2800 km southeast of Tokyo, Japan and 2400 km east-southeast of Manila, Philippines. Guam is the largest of the Mariana Islands with a land surface of about 550 km^2. Guam is divided into two equally-sized physiographic provinces separated by the Pago-Adelup Fault (Figure 3). The northern province is an uplifted carbonate plateau with near-vertical cliffs at the coast. The southern province is mostly volcanics and volcanoclastics with isolated limestone bands. The only sizable surface streams on Guam are located on the southern half of the island (Mink and Vacher, 1997).

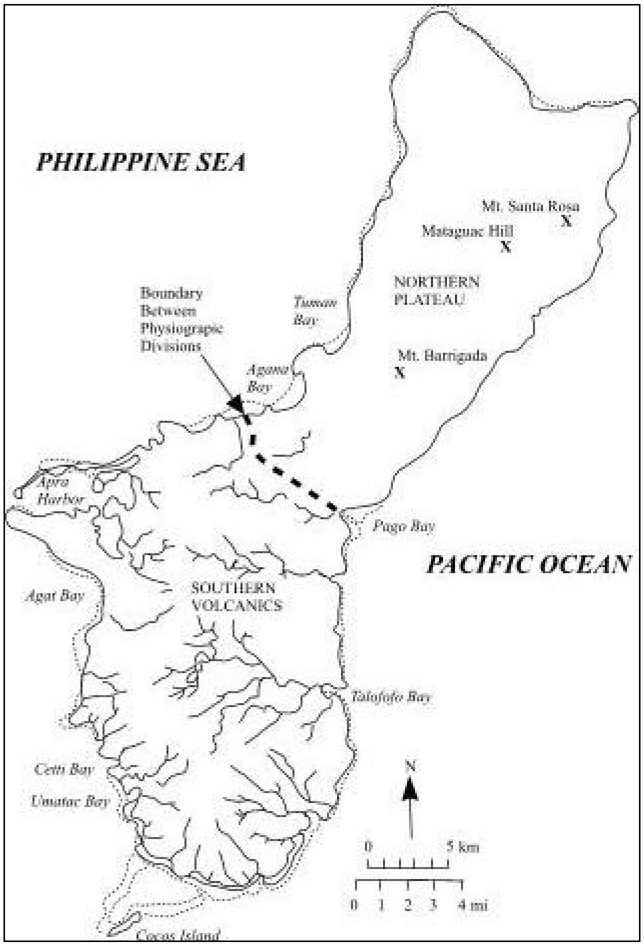


Figure 3: Major physiographic provinces of Guam (Modified from Mink and Vacher, 1997)

Jenson et al. (in press) further subdivided the physiographic provinces of Guam into five divisions: Northern Plateau, Basement Outcrops, Southern Coast, Southern Interior Basin, and Southern Mountain Range (Figure 4).

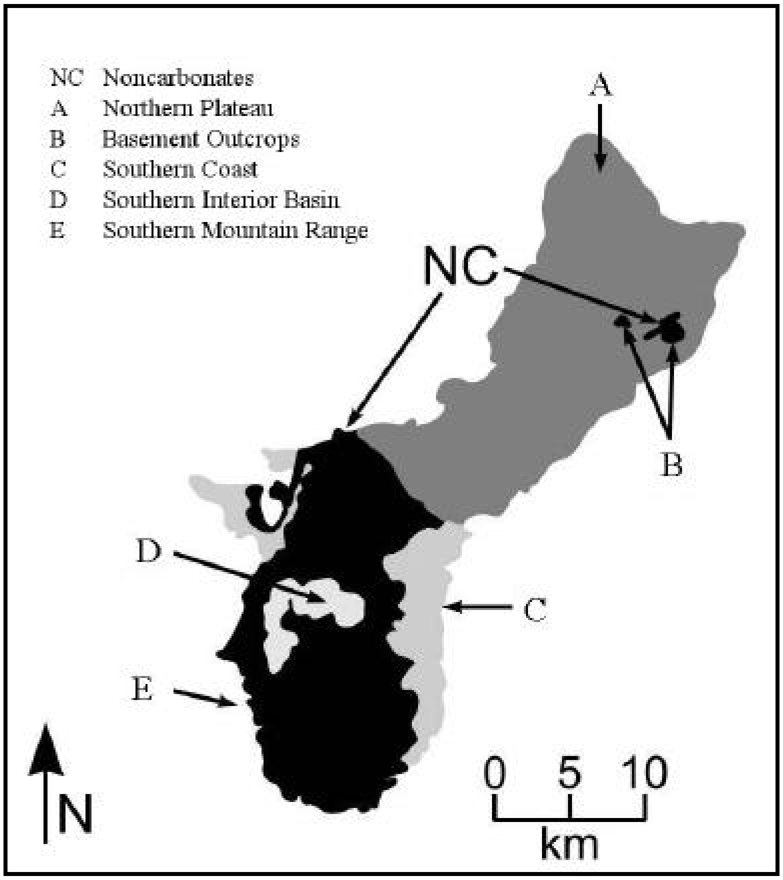


Figure 4: Physiographic map of Guam (Modified from Jenson et al., in press)

Rota is located about 80 km north of Guam and has a surface area of about 96 km^2 and a coastal perimeter of about 52 km. There are six physiographic provinces in three Regions. The regions are: *Sinapalo* Region, *Sabana* Region, and the *Taipingot* Peninsula. Sugawara (1939 [1949]) described the physiographic provinces in terms of their terrace level. The six terrace levels described are: *Sabana*, *Aburataruga*, *Shinaparu*, *Lugi*, *Taragaja*, and *Mirikattan*. Keel (2005) divided the island into five regions: *Sabana*, *Talakhya*, *Sinapolo*, *Taipingot* Peninsula (Wedding Cake) and Songsong Village (Figure 5). Stafford et al (2002) reported volcanic outcrops in the

Sabana and *Talakhaya* regions with the only surface streams occurring on the *Talakhaya* (Keel, 2005).

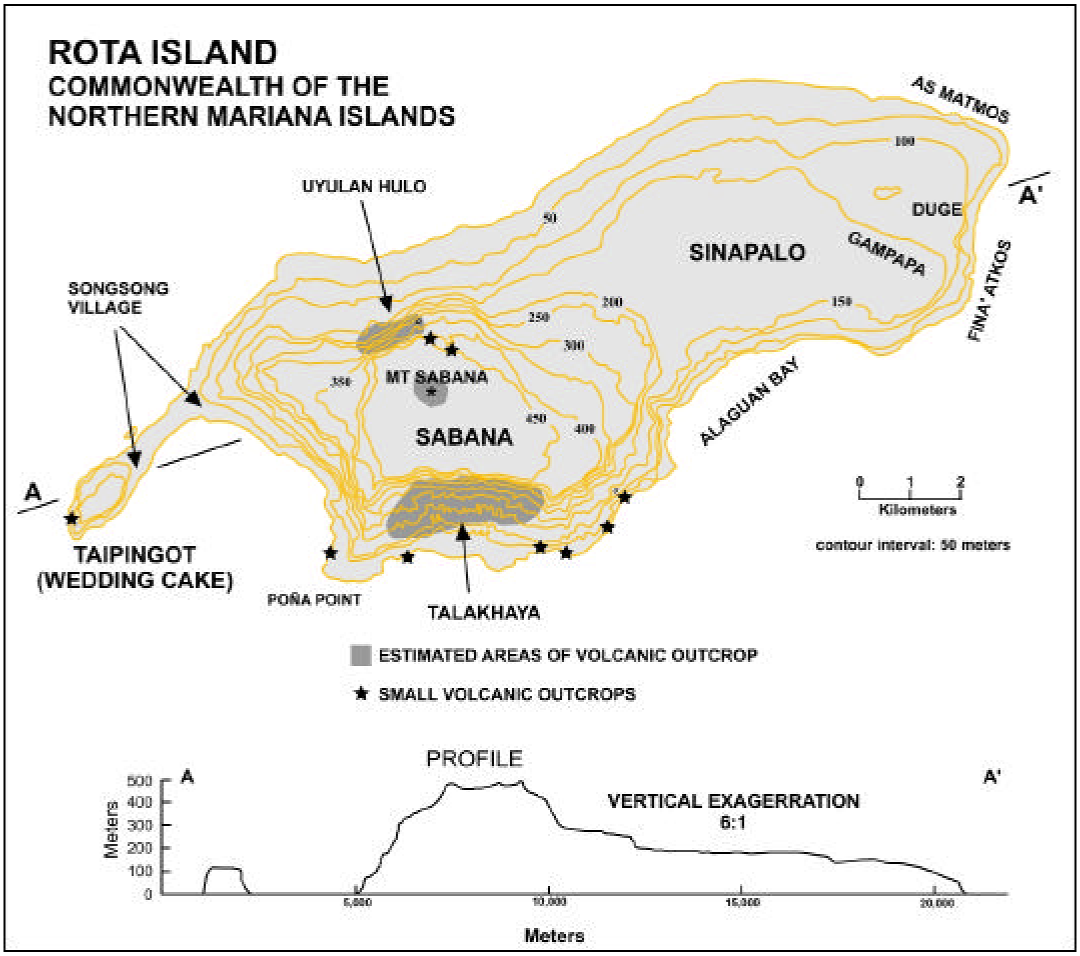


Figure 5: Physiographic map of Rota (Keel, 2005)

Aguijan has only about 7.2 km^2 of island surface, all of which is exposed carbonates. Tayama (1936) and Stafford (2003) described the geology of Aguijan as being composed of Miocene and Plio-Pleistocene carbonate rocks resting on an Eocene volcanic edifice. There are three concentric terraces on Aguijan at elevations of 0-50 m, 50 – 100 m, and 100 – 150 m (Figure 6). There are no surface streams or beaches on Aguijan (Jenson et al., in press).

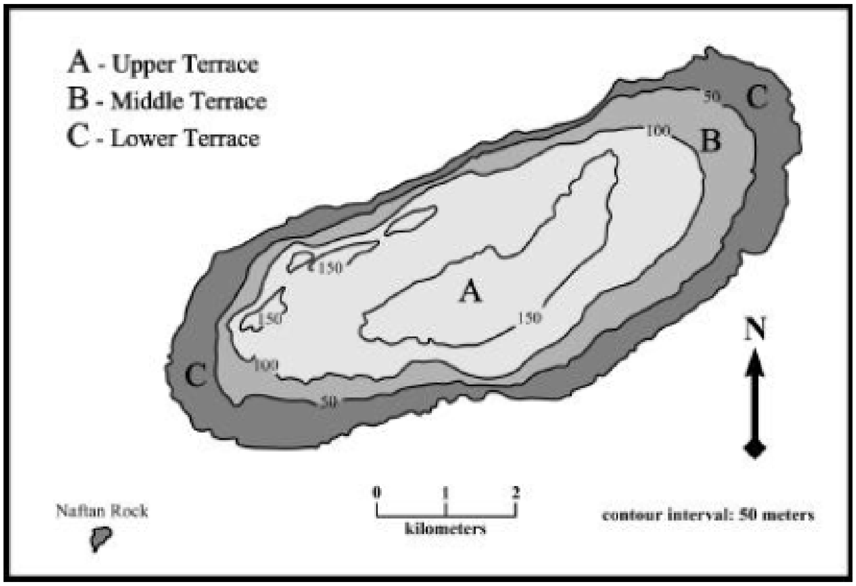


Figure 6: Physiographic map of Aguijan (Stafford et al., 2002)

Tinian covers 102 km^2, and is the third largest of the Mariana Islands. Cloud et al. (1956) performed the most recent geologic study of the island. The island was divided by Doan et al. (1960) into five provinces separated by high-angle faults: Northern Lowland, North-Central Highland, Central Plateau, Median Valley, and Southeastern Ridge (Figure 7). Stafford et al. (2002) reported four volcanic outcrops on Tinian: near: *Sabanettan Mangpang*, *Bañaderon Lemmai*, and *Laderan Apaka* (Fig 7). Allogenic streams flowing off of *Bañaderon Lemmai* provide for point source recharge into the karst system.

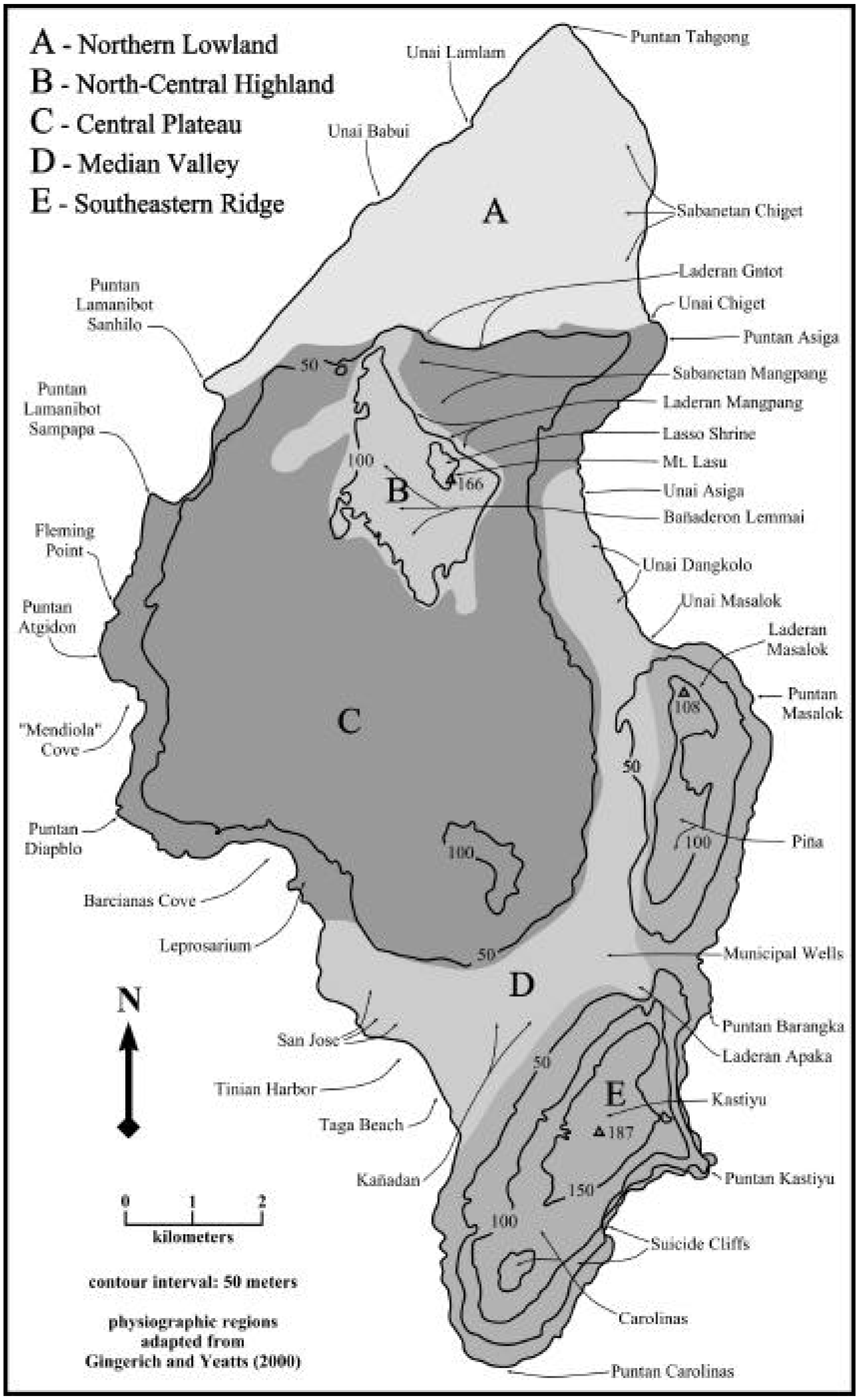


Figure 7: Physiographic map of Tinian (Stafford, 2003)

Saipan is the second largest of the Mariana Islands and the largest of the 14 islands in the Commonwealth of the Northern Mariana Islands (CNMI) at 124 km^2. The island is divided into five provinces: Axial Uplands, Coastal Plain, Donni Clay Hills Belt, Coastal Fault Ridges, and Low Platform and Terraces (Figure 8) (Doan et al., 1960). Saipan is the type example for the Complex Island in the Carbonate Island Karst Model (see below) because of its complex and highly variable geology, lithology, and hydrology present (Jenson et al., in press). The faulting and interfingering of units creates a fragmented, sometimes perched, water table. In addition, the faulting can place carbonates next to non-carbonates and force the phreatic water to take circuitous routes to the sea, create confined (artesian) conditions or even isolate portions of the fresh-water lens (Mylroie et al., 2004).

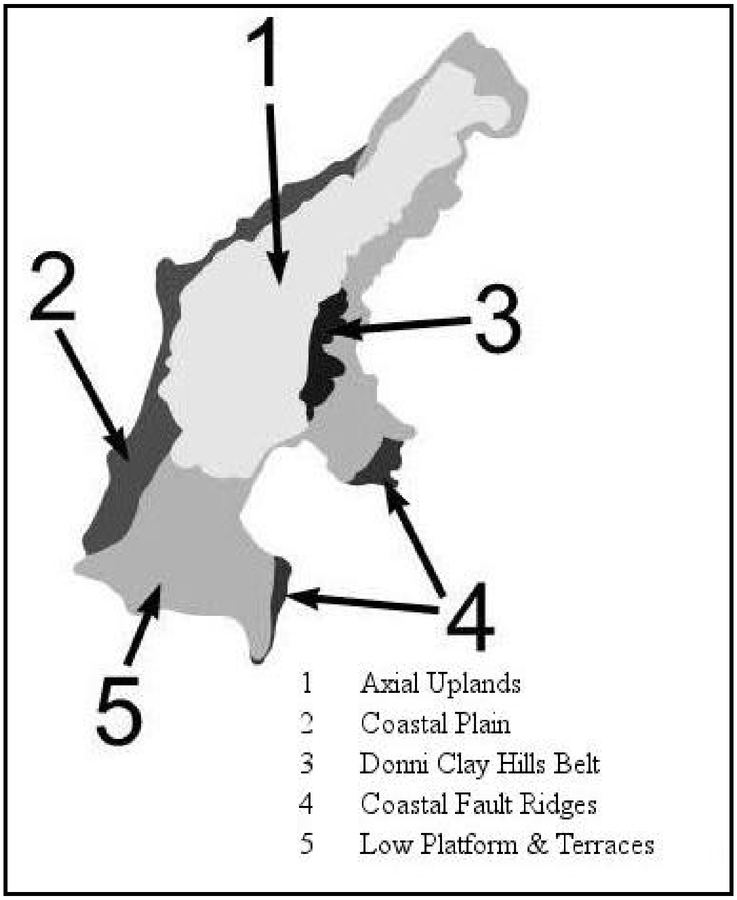


Figure 8: Physiographic map of Saipan (Modified from Jenson et al., in press)

No systematic survey of Farallon de Medinilla, which is located approximately 84km north of Saipan, has been performed because of its remote location and its use as a military munitions training area (Jenson et al., in press).

History

The first recorded settlement of the Mariana Islands was by the Chamorro people at around 1500 BCE (before common era). Ferdinand Magellan was the first European to visit the Marianas in 1521. In claiming the islands for Spain, Ferdinand

Magellan named the islands Islas de los Ladrones (Thief Islands). In the early 1600's the islands were renamed Islas de las Marianas (Mariana Islands) after Maria Ana of Austria. During Spain's almost four centuries of control of Micronesia (Mariana Islands, Caroline Islands, and Palau), migration occurred from the Caroline Islands to the Marianas. The Chamorro population was decimated during Spanish control due to disease, forced migration, and a process called "reduction" where the Spanish missionaries forced many Chamorro to migrate from their home island to Guam in order to control them and convert them to Christianity (Coomans, 1997).

America took control of Guam in 1898 during the Spanish-American War and, until captured by Japan in 1941, was administered by the U.S. Navy. Spain sold the rest of Micronesia to Germany in 1899 to help pay for the costs incurred during the war. It was during German control that the agricultural and fishing economies developed, partly due to additional immigration from Carolina islands such as Chuuk and Yap, and Japanese from nearby islands such as Okinawa. The Germans controlled the islands until World War One (Hunt and Wheeler, 2000).

In 1914, at the start of World War One, Japanese troops took control of the Mariana Islands. The Japanese cleared between 58% and 90% of the land area to create extensive sugar cane plantations (Bormann, 1992; McClure, 1977). After World War One, the League of Nations officially recognized Japan as the administrator of the islands. The Japanese continued to control the islands until World War Two, when the United States military took control of the islands. Guam, Saipan, and Tinian were taken in 1944 in some of the bloodiest battles of the war. The other Mariana Islands were acquired as part of Japan's surrender conditions. After taking control of Tinian, the U.S. military established a large airfield, called North Field, covering the northern third of the island, for the purpose of bombing the Japanese mainland. For a period during the war, North Field was the busiest airport in the world with pairs of B-29's taking off every 45 seconds on mission days. In fact, the planes carrying the only two atomic bombs ever used in a military campaign, Fat Man and Little Boy, took off from the Tinian airfield (McClure, 1977).

In 1976 the Commonwealth of the Northern Mariana Islands (CNMI) was formed by an act of Congress. The CNMI consists of all of the Mariana Islands except Guam. The CNMI consists of three municipalities: Rota, Saipan, and Tinian. Uninhabited Aguijan is part of the Tinian municipality. The CNMI is unique among the world's countries as it is self-governing for the most part but is part of the United States of America. Many U.S. government agencies, such as US Postal Service, National Park Service, USGS, and USDA operate in the CNMI. The services of U.S. government and the right to vote in U.S. presidential elections are provided in exchange for a lease of 75 km^2 of land, including about 2/3 of Tinian (Hunt and Wheeler, 2000). While the majority of Tinian is still under U.S. military control, small farms and tourism provide income for the island's approximately 2000 residents (Bormann, 1992).

Guam is currently a U.S. Territory that is administered by the Department of the Interior. However, from 1944 through 1962, access to Guam was restricted for military security (Rogers, 1996). After the restrictions were lifted, the economy of Guam improved, largely due an influx of Japanese tourist dollars

Climatology

The Mariana Islands have a tropical marine climate with a year-round average temperature of 80°F. Rainfall averages around 2,000 mm/yr with most of the rain coming in the wet season that starts in June and runs through December (Carruth, 2003).

Vegetation

According to Mueller-Dombois and Fosberg (1998) the primary species on volcanic soils is *Miscanthus flourdulus*, a type of sword grass. However, *Miscanthus* was found growing on limestone soils on Saipan, so it is not one hundred percent predictive of soil type. Other species are found on volcanic soils, mostly in ravines. They are: *Sphenomeris chinenis*, *Dicranopteris linearis* (a branching fern), *Mimosa invisa* (a prickly herb), *Pennisetum polystachyon* (mission grass), *Areca catechu* (bezel palm), *Hibiscus tiliaceaus* (sea hibiscus), *Pandanus tectorius* and *P. dubius* (screw pines), *Ficus prolixa* (strangler fig), *Glochidion mariannensis*, *Premna serratifolia* and *Casuarina equisetifolia* (ironwood) and regions of coconuts and bamboo. Mixed forests dominate the limestone terraces on all of the islands and terrace edges are dominated by a variety of shrubs. The primary species on limestone soils are summarized in Table 1.

Table 1: Common vegetation on limestone soils (Mueller-Dombois and Fosberg, 1998)

Scientific Name	Common Name	Scientific Name	Common Name
Acrostichum aureum	Swamp Fern	Neisosperma oppositifolium	
Artocarpus	Breadfruit	Osmoxylon	
Barringtonia asiatica	Sea Poison Tree	Pandanus dubius	Screwpine
Barringtonia racemosa	Fish Poison Tree	Pandanus tectorius	Screwpine
Casaurina equisetifolia	Ironwood	Paspalum distichum	Knotgrass
Chromolaena odorata	Siam Weed	Pemphis acidula	Small-leafed Mangrove
Clerodendrum inerme	Seaside clerodendrum	Phragmites karka	Tall Reed
Cynometra ramiflora	Gulos	Phyllanthus marianus	Leafflower
Excoecaria agallocha	Milky Mangrove	Pisonia grandis	Grand Devil's-claws
Fagraea bertnensis		Pisonia umbellifera	Bird-catcher Tree
Ficus	Rainforest Fig	Pithecellobium dulce	Monkeypod
Gossypium	Cotton	Poptarus	
Hedyotis foetida	Smelly Hedyotis	Premna serratifolia	Premna
Hedyotis strigulosa	Paodedo	Psydrax (Canthium) odoratum	
Hernandia labyrinthica		Scaevola taccada	
Hernandia nymphaeifolia	Lantern Tree	Sophora tomentosa	Necklace Pod
Hibiscus tiliaceus	Sea Hibiscus	Stenotaphrum micranthum	Beach Grass
Laportea Gaud	Laportea	Terminalia	Tropical Almond
Leucaena leucocephala	Wild Tamarind (aka tangantangan)	Thespesia populnea	Portia Tree
Macaranga	Parasol Leaf Tree	Thuarea involuta	Kuroiwa Grass
Morinda citrifolia	Indian Mulberry	Tournefortia argentea	Velvetleaf soldierbush
Myoporum boninense		Zoysia matrella	Manila Grass

CHAPTER III

KARST DEFINITIONS

Holokarst

Holokarst is a type of karst landform where the whole of the drainage basin lies on carbonate rocks and all recharge is therefore autogenic (from within) as a result of direct capture of meteoric recharge. Surface streams are uncommon, and where they do exist, are infrequent, short, and often ephemeral. Nearly all of the drainage is in the subsurface and recharge is typically diffuse (White, 1988).

Fluvialkarst

Fluvialkarst is differentiated from holokarst in that some or all of the drainage basin recharge flows over non-carbonate rocks. Such drainage is called allogenic (from without). Where surface streams flow over the non-carbonates and meet the carbonates, swallets (a.k.a., swallow holes, insurgences) are frequently found. In the initial stage of swallet formation, only a small portion of the surface stream is diverted into the underground and the rest continues across the carbonates. As the initial pathway is widened by dissolution, more and more of the stream is diverted until there is no surface drainage on the carbonate portion of the drainage basin, except in periods of extremely high runoff. In the long-term, all drainage from the non-carbonates may be diverted underground into the carbonates (White, 1988).

Eogenetic

Eogenetic rocks are young rocks that have not undergone the mesogenetic burial and diagenesis that creates the dense, microcrystalline limestones found in most interior continental settings. Because they have not undergone mesogenetic burial, much of the initial primary porosity is maintained both in the matrix and as ubiquitous vugs. In spite of the high depositional porosity, these eogenetic rocks have a low initial permeability. However, the flow of vadose and phreatic waters through the carbonates does rearrange the porosity such that there are preferred vadose and phreatic flow lines in the subsurface (Vacher and Mylroie, 2002). In eogenetic karst, the flow of meteoric water causes the diagenesis and cementation of the calcite grains. Secondary porosity forms concurrently with the diagenesis (Vacher and Mylroie, 2002).

Teleogenetic

Teleogenetic rocks are those that have been subject to mesogenetic burial but are now subject to surface processes, including erosion. Much of the porosity of teleogenetic rocks is due to the presence of bedding planes, fractures, and faults (Vacher and Mylroie, 2002).

Epigenic

Epigenic processes are tied to the surface hydrology. Allogenic or Autogenic water, driven by gravity, moves from recharge areas through the subsurface directly to nearby springs. Carbonic acid (H_2CO_3), created by the dissolution of CO_2 in water, is the primary acid responsible for the dissolution of calcite in these settings (Palmer, 1991).

Hypogenic

Hypogenic processes occur where there is a decoupling from the surface hydrology. Hypogenic caves form where aggressive deep phreatic waters meet limestone, or additional aggressivity is created by the mixing of waters with different CO_2 conditions. Carbonic acid and hydrosulfuric acid, formed at depth by either redox reactions or igneous activity, are primarily responsible for the dissolution of calcite in hypogenic processes (Palmer, 1991).

Epikarst

Epikarst, or surface karst, forms due to the dissolutional sculpting (karren) of the limestone within the first meter or so of the surface. Because 90% of the dissolution potential of rainfall is used in the first 30 minutes of contact with carbonates (White, 1988), the limestone in areas with high annual rainfall totals tends to be highly sculptured. In coastal areas the activity of sea spray may create highly sculpted landscapes because of the action of biologics (Viles, 1988; Folk et al, 1973), but others think the biological impact is overstated (Mylroie and Carew, 1995b). Taborosi et al (2004b) believes karren features to be polygenetic, due to one or more of the following factors: mixing dissolution due to the mixing of meteoric water and salt spray, salt weathering, and biological weathering operating on diagenetically immature eogenetic carbonate rocks.

CHAPTER IV

ISLAND KARST

Carbonate Island Karst Model

Mylroie et al. (2001, 2004) developed the Carbonate Island Karst Model (CIKM) to explain the types and locations of karst features found in carbonate islands. The basic elements of the CIKM are:

1. Eogenetic carbonate rocks
2. The fresh-water/salt-water boundary creates a zone of enhanced (mixing) dissolution and produces organic-trapping horizons at both the upper and lower boundaries of the fresh-water lens.
3. Vertical movement of the fresh-water lens due to glacio-eustatic sea level changes.
4. Overprinting of glacio-eustacy by subsidence or uplift.
5. The classification of islands into one of four categories based on the relative positions of the non-carbonate basement rocks and sea level.

The mixing of waters with different initial conditions created many of the caves in carbonate islands. Because the dissolution curve of $CaCO_3$ is convex upwards when two waters of different initial conditions are mixed, the aggressivity of the water is renewed and additional $CaCO_3$ can be dissolved. Figure 9 is a graphic representation of the dissolution curve, presenting Ca^{++} concentration as a function of carbonic acid

(H_2CO_3). Points above the line representing oversaturated conditions, points below the line representing undersaturated conditions, and the line itself being the saturation curve. If saturated waters at points A and B mix, the resulting mixture is represented by the straight line between A and B, depending on the relative amounts of the waters that were mixed. Since every point along the line between A and B represents an unsaturated condition, additional dissolution of $CaC0_3$ can occur. If the mixing of A and B results in mixture C dissolution can occur to point D. The additional amount of calcite dissolved can be computed as C'-D'. Also, the greater the difference in the initial H_2CO_3 concentrations the greater the dissolution potential of the resulting mixture (Dreybrodt, 2000).

This process occurs even if the two waters were initially saturated with respect to $CaCO_3$. It is the differences in CO_2 partial pressures of the mixed waters that is most important, rather than the differences in salinity, when determining the amount of additional aggressivity that occurs (Vacher and Mylroie, 2002).

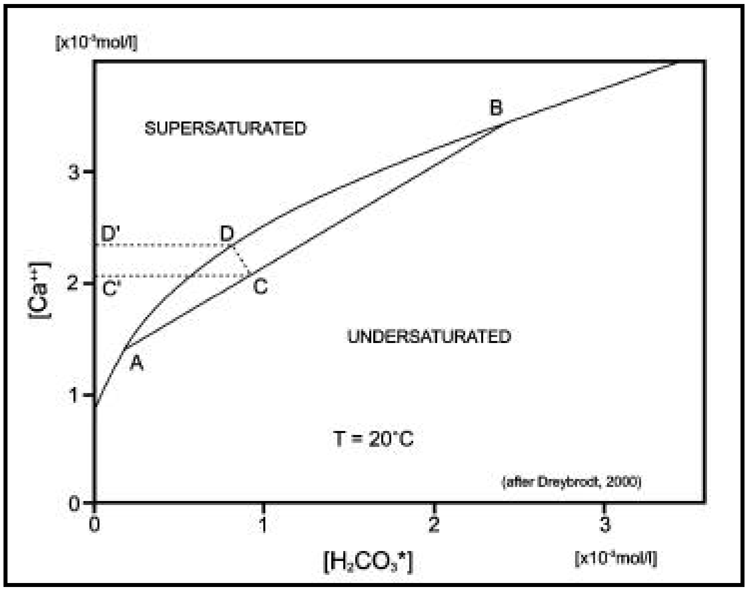


Figure 9: Calcite Solubility versus Carbonic Acid Concentration (Keel, 2005, after Dreyboldt, 2000)

A fresh-water lens is a lens-shaped body of fresh-water that floats on top of the underlying phreatic marine water. The fresh-water floats on the marine water due to a 1/40-density contrast between the two waters (Figure 10). The thickness of the lens depends on the amount of recharge and the permeability of the rock. All other things being equal more recharge results in a thicker lens. Greater permeability in the rock decreases the thickness of the fresh-water lens because less head pressure is required to push the fresh-water to the sea. In an idealized situation, the fresh-water lens would be thickest at the center of the island and gradually pinch out at the edge of the island (Raeisi and Mylroie, 1995).

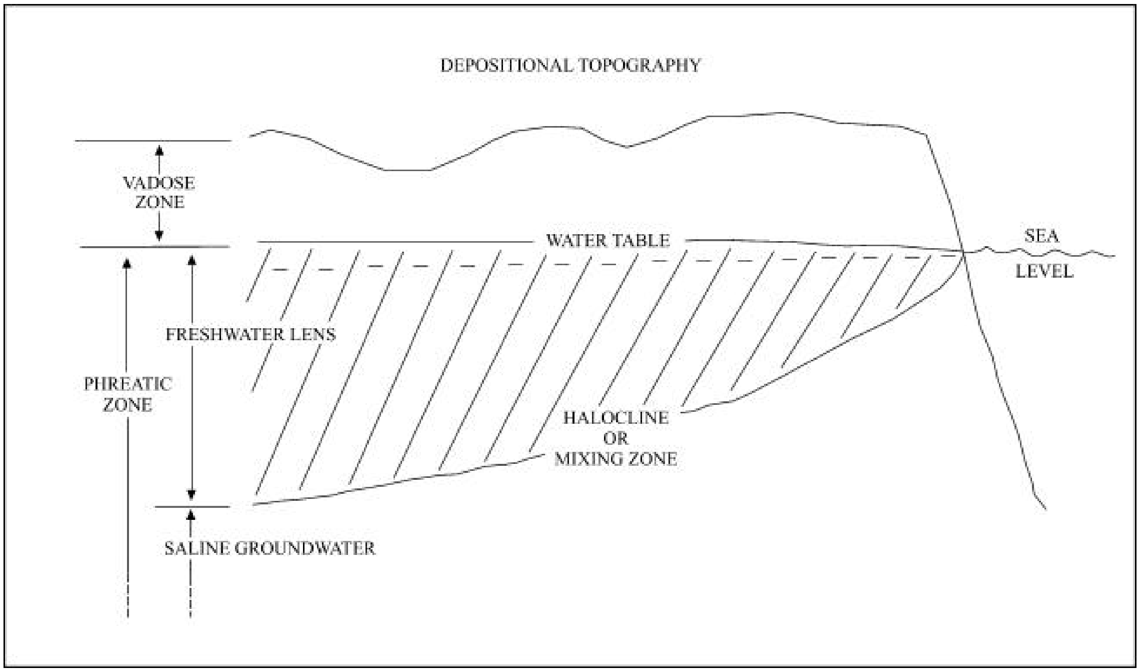


Figure 10: Representation of a fresh-water lens on a carbonate island showing the hydrologic environments from the land surface to the saline groundwater (Mylroie and Carew, 1995b)

According to Mylroie and Carew (1995a), zones of additional aggressivity and mixing dissolution occurs in two places: at the top of the fresh-water lens where vadose and phreatic waters mix; and at the bottom of the fresh-water lens due to the mixing of fresh and saline waters (Figure 10). The fresh-water/salt-water boundary is called the halocline. This boundary may be sharp or up to several meters thick, with a zone of brackish water existing between the phreatic fresh-water and the seawater. Relative density differences occur at the top and bottom of the fresh-water lens, allowing organics to accumulate. The decay of these organics release CO_2 to the lens boundary, supporting more dissolution. If sufficient organics exist, oxygen is used up and anoxic hydrogen sulfide (H_2S) is released, leading to additional dissolution, especially if enough oxygen is later present to oxidize the H_2S to H_2SO_4 (Mylroie and Carew, 1995b).

Sea level in carbonate islands is controlled by two factors: glacio-eustacy, and tectonics. With sea-level change there is a concurrent change in the position of the fresh-water lens. Glacio-eustacy has changed sea level, and therefore the position of the fresh-water lens, by over 100 m during the Quaternary. The glacio-eustacy has been overprinted in the Mariana Islands by an average tectonic uplift of 1.8 m since the mid-Holocene (Dickinson, 1999). Because the position of the fresh-water lens changes, so does the elevation of mixing-zone dissolution.

The position of any underlying non-carbonate rocks is also important in the CIKM. Recently Mylroie et al. (2004) classified carbonate islands by the position of the non-carbonate basement rocks relative to sea level and the land surface. Each classification represents an end-member and a single island may be partitioned such that different portions of the island fall into different categories. The classification of an island as either Simple or Carbonate-Cover depends entirely on the relative position of the non-carbonate rocks and sea level, provided that no non-carbonate rock is subaerially exposed, as shown in Figure 11. If only carbonate rocks exist above sea level the island is classified as a Simple Carbonate Island (Figure 11a). If non-carbonate rocks extend above sea level but are mantled by carbonates, the island is a Carbonate-Cover Island (Figure 11b). If the non-carbonates are subaerially exposed, the island is classified as either a Composite or Complex Island depending on the presence of faulting and interfingering of units. Little interfingering of units or faulting exists in

Composite Islands (Figure 11c). The interfingering of units and faulting causes additional partitioning of the fresh-water lens in Complex Islands (Figure 11d).

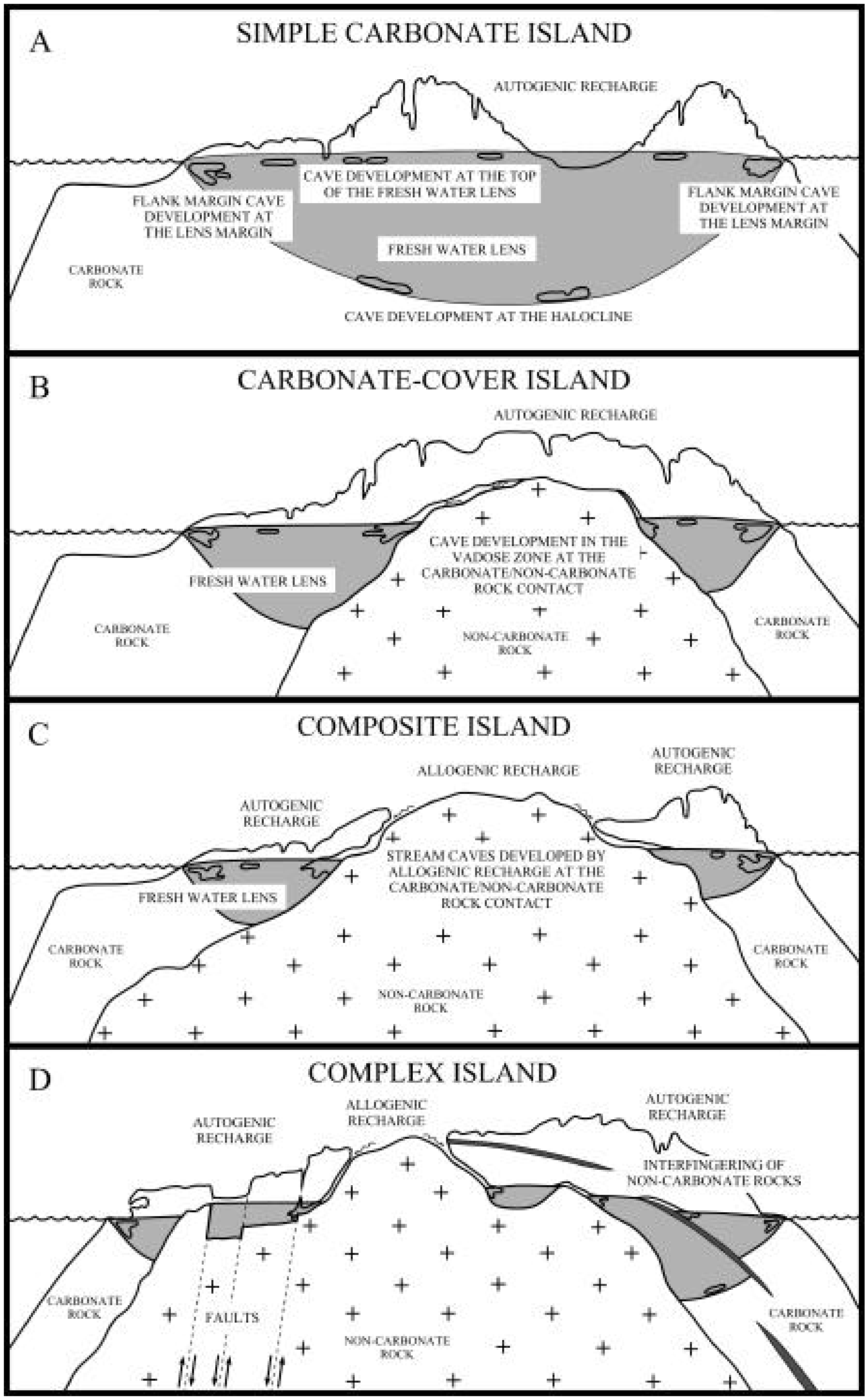


Figure 11: Carbonate Island Karst Model (CIKM) (adapted from Mylroie et al., 2002)

Subsidence, uplift and glacio-eustatic sea-level change may cause an island to change from one classification to another. For example, if either uplift or a glacio-eustatic sea-level fall causes the fresh-water lens to drop onto the basement rocks, an island that was previously classified as a Simple Carbonate Island would be reclassified as a Carbonate-Cover Island. Conversely, if glacio-eustacy or subsidence causes a local sea-level rise, or if the fresh-water lens is lifted above the non-carbonate rocks, a Carbonate-Cover Island may become a Simple Carbonate Island.

The CIKM classification of islands as Simple, Carbonate-Cover, Composite, or Complex is important to understanding of the hydrology and karst of an island. Whereas in the case of a Simple Carbonate Island the fresh-water lens is not partitioned by the presence of non-carbonates, it is in the case of Carbonate-Cover, Composite, and Complex Islands. If only carbonate rocks are present on the surface (Simple and Carbonate-Cover Islands) all of the ground-water recharge is autogenic and only holokarst features form. Fluvialkarst features can form when non-carbonates are subaerially exposed and some of the ground-water recharge is allogenic (Composite and Complex Islands).

In the simplest case, Simple islands have a single, unbroken, fresh-water lens extending beneath the whole island. However, in arid regions, the lens may be partitioned due to the presence of lakes containing upconed saline waters.

The CIKM predicts that two types of mixing-zone caves will form: flank-margin caves, and banana holes. In addition, pit caves, fissure caves, recharge caves, and contact caves may be present (Figure 12).

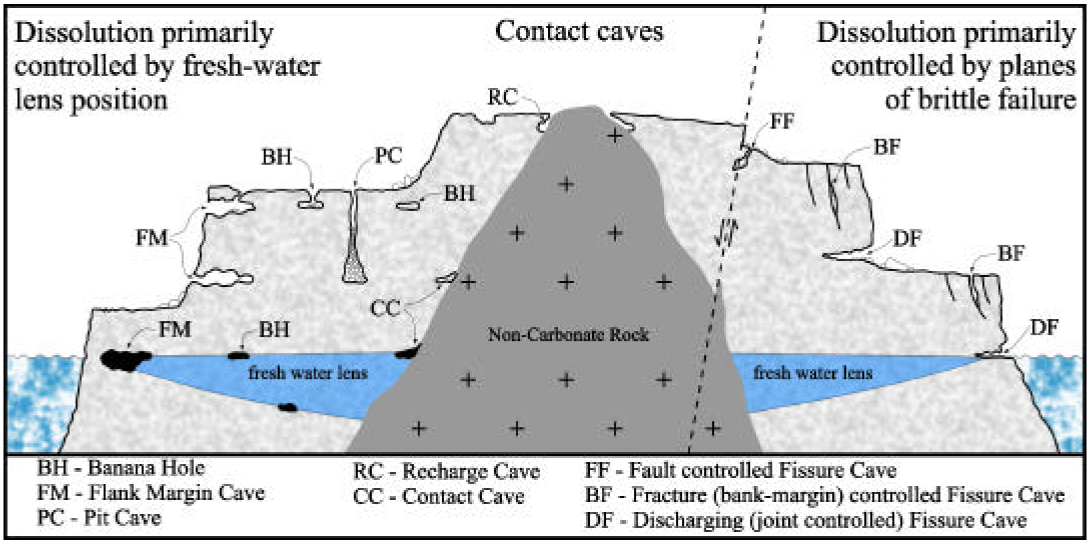


Figure 12: Conceptual model of cave types that form in eogenetic rocks on carbonate islands (Stafford, 2003)

Flank Margin Caves

Flank margin caves form at the flank of the enclosing landmass at the margin of the fresh-water lens where the top of the fresh-water lens meets the bottom of the fresh-water lens. It is in this zone where waters with three different initial conditions (fresh-water vadose, fresh-water phreatic, and marine phreatic) mix and the largest caves in the CIKM form. It must be stated that flank margin caves are not conduits, but simple mixing chambers. In addition, they are decoupled from the surface hydrology and are therefore classified as hypogenic caves (Mylroie and Carew, 1990; Palmer, 1991).

Pit Caves

Pit caves are where vertical shafts characterized by a width-to-depth ratio of greater than one and have been interpreted to be vadose fast-flow routes by Harris et al.

(1995). They drain meteoric water collected in the epikarst to the phreatic zone. Pit caves may intersect the water table, but commonly stop several meters above it. This may be due to the autogenic recharge using up its dissolutional potential near the surface. Water continues down to the water table as diffuse flow (Mylroie and Carew, 1995a).

The drainage of phreatic waters reorganizes the porosity of eogenetic limestones into preferred flow routes (Vacher and Mylroie, 2002). At the boundaries of these preferred flow routes there is a zone of lower porosity. Pit caves allow vadose waters to cut across these zones of lower porosity and reach the current phreatic zone more quickly (Mylroie and Carew, 1995b).

Banana Holes

Banana holes are shallow holes with a width-to-depth ratio of less than one (Harris et al., 1995). Their name derives from their use in the Bahamas where they are frequently used to grow banana trees and other agricultural crops (Jackson and Bates, 1997). Banana holes are phreatic features that form at the top of the fresh-water lens due to the mixing of vadose and phreatic waters and are thus better-called water-table caves. When they form at shallow depths, they are prone to roof collapse and subsequent surface expression. As with other surface depressions, they are natural collectors of both water and vegetative matter (Mylroie et al., 1995).

Banana holes are not common in the Mariana Islands because uplift has put thick masses of limestone between the lens and the surface, and collapse is minimal.

Fissure Caves

Fissure caves result from enlargement along a joint, fracture, or fault (White, 1988). They may form perpendicular or sub-perpendicular to the coast, parallel to the coast due to cliff-margin or bank-margin failure or along a fault plane. Fissure caves that form perpendicular to the coast have been interpreted to be related to tension-release failures (Stafford et al, 2005). Like pit caves, they provide fast-flow routes through the subsurface. Unlike pit caves, they may act as either recharge or discharge features (Stafford et al., 2002). Fissure caves may form due to the movement of large blocks of limestone that have slid due to the weathering of the underlying volcanics to clay, dissolutional widening of high angle normal faults, or dissolutional widening of fractures. Only fissures caused by bank-margin failure and sliding of large blocks of limestone have a significant mechanical component to their genesis. Because of these two distinct modes of genesis, only those caves that formed due mechanical movement are called fissure caves. Caves that formed due to the dissolutional widening of a fracture at the lens margin are called mixing-zone fracture caves (Keel, 2005).

Contact Caves

Contact caves are a general classification of caves that form at the contact of the limestone and the non-carbonate basement rocks. Vadose water moves downward along the contact and forms cave passages; and the water will likely still be aggressive when it hits the water table. The mixing of this aggressive water with the phreatic waters at the inner margin of the lens will likely create a zone of enhanced dissolution. So far no cave chamber has been unequivocally identified as a contact cave that formed at the top of the fresh-water lens (Taborosi et al., 2004a), but strong evidence exists.

Recharge Caves

Recharge caves, also known as stream caves, form where a stream, or part of a stream, is diverted into the subsurface. Recharge caves are a type of contact cave that form where the stream sinks at the contact of the limestone and the bordering non-carbonates. The catchment area for the stream is usually on the volcanics and is unable to efficiently infiltrate, therefore surface streams form. These surface streams channel water down to the carbonate/non-carbonate contact where an allogenic point recharge source occurs (Mylroie et al., 2001).

Closed Depressions

A closed depression is any depression from which there is no surface outlet. They may be classified as either dissolutional, natural constructional or anthropogenic. It may be difficult to accurately classify a closed depression as either dissolutional or constructional without detailed field examination. Furthermore, many natural closed depressions have been anthropogenically modified for use as quarries, landfills, drainage ponds, or storage ponds, making accurate classification even more difficult (Mylroie et al., 1999). In Simple Carbonate Islands, constructional closed depressions are the most common form (Mylroie and Vacher, 1999). Constructional closed depressions may be caused by dune swales in eolianites, variations in reef growth (later subaerially exposed), and other variations in the depositional environment. Dissolutional closed depressions are often small on carbonate islands due to the fact that autogenic recharge tends to be diffuse rather than focused, but large dissolutional closed depressions may form where there is allogenic recharge and sinking streams focus the recharge (Mylroie et al., 1999).

CHAPTER V

KARST DATABASE

Relational Database Design

In 1970, Codd introduced the simple idea of a database that consists of relations. He called such a database a relational database. In a relational database, relations are called entities or tables. Each table stores information about a real-world object or concept. For example, a relational karst database would have individual tables for caves, entrances, springs, sinkholes, and other karst-related objects. Each table in a relational database is given a name that describes its contents, such as CAVES, ENTRANCES, SPRINGS, SINKHOLES, etc. In much of the relational database world, the convention is to use uppercase letters when naming objects. Table names are plural to show that they can contain multiple instances of a given object type.

Each entity, or table, in a properly designed relational database has specific properties. These properties are called attributes, and are created as columns in the table. Each attribute has a data type, such as integer and string, and often a restricted set of values, called a domain. An example of a domain applicable to a karst database is cave type. Domain values might include: active epigenetic, relic epigenetic, hypogenic, pseudokarst, and others. As with tables, each attribute is given a name. Attribute names must be unique within a table, but may be duplicated across tables. For example, the CAVES, ENTRANCES, SPRINGS, and SINKHOLES tables may all contain a NAME attribute, but the NAME attribute may only occur once within each of the tables. Attribute names are singular to show that each attribute may contain only a single value for a given row.

Data are contained with tables as a set of tuples, or rows. Unlike tables and columns, rows are not named in relational databases. No two rows in a table may have an identical set of attribute values. In fact, most tables can be uniquely identified by a small subset of the attributes, such as a CAVES table might only need the NAME attribute to uniquely identify each row. Such a column, or subset of columns, is called a key. A table should have at least one key, but may have many keys. The key that is used most often to identify an individual row is called the primary key. Other keys that may exist are simply called secondary keys. Often, when multiple attributes are in the key, or when the key may need to be updated, an artificial key is created to ease administration and data maintenance. Artificial keys are usually created with a data type of integer and are often named ID, or more frequently, the table name (singular) is suffixed with "id", as in CAVE_ID, ENTRANCE_ID, and SPRING_ID. If an artificial key is created, it is usually used as the primary key and other keys are created as secondary keys. Adding one to the previous high value, or using a proprietary database mechanism for creating a unique numerical series, is the usual mechanism for populating artificial keys. In order for a column, or set of columns, to be used in a primary or secondary key, the column must be defined as required, thus prohibiting NULL (or no data) values from being stored in the attribute.

Excepting in the simplest of cases, there are relationships between each of the tables in a relational database. As previously stated, in a karst database there may be a relationship between caves and entrances. Namely, each cave has at least one entrance. This is an example of a one-to-many relationship. Other types of relationships include one-to-one and many-to-many relationships. One-to-one relationships are not used frequently, usually only if a table has a very large size or an unusually large number of attributes. They are created in the same way as one-to-many relationships. One case where a one-to-one relationship may be used is if a map of the cave is stored in the database. Because cave maps can be large relative to the rest of the cave data, a separate table may be created to store just the cave maps and a one-to-one relationship be created between the CAVES and the CAVE_MAPS table. Many-to-many relationships are more common, but most Relational Database Management Systems (RDBMS) do not directly support their implementation and therefore need to be resolved before they can be implemented.

In one-to-many relationships one table is called the “parent” table and the other is called the “child” table. In general, the table on the “one” side of the relationship is called the parent table and the table on the “many” side of the relationship is called the child table, much as a parent can have many children in biological relationships. In the cave-entrance example previously used, the CAVES table is the parent table and the ENTRANCES table is the child table. In order to define a relationship between tables, the primary key attributes from the parent table are copied to the child table and a relationship, called a foreign key relationship, is created (Figure 13). As with primary key attributes, foreign key attributes are not allowed to contain NULL values. Doing so prevents “orphan” rows from being created in the child table. An orphan row is where there is a row in the child table without a corresponding row in the parent table. Continuing the karst example, creating such a foreign key relationship prevents entrances from being created without first having a corresponding row in the CAVES table.

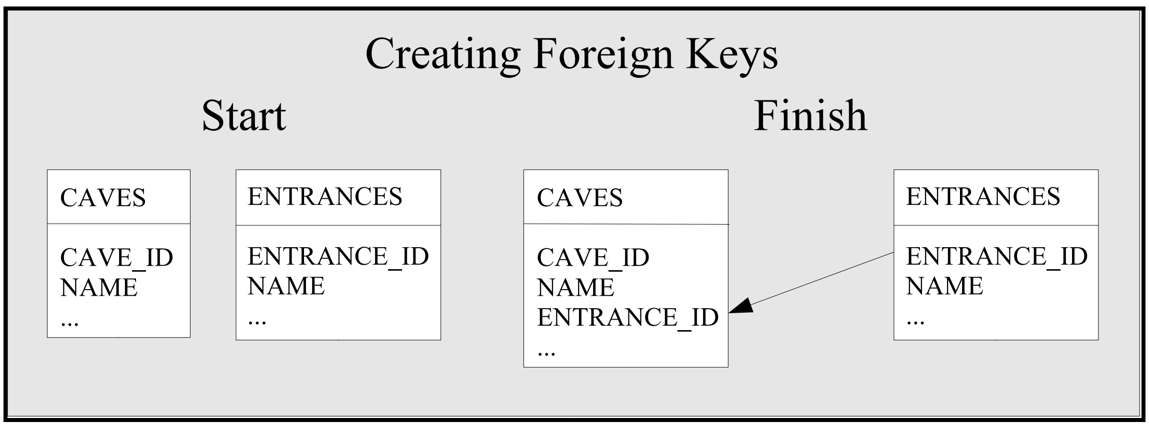


Figure 13: Process of creating Foreign Keys

As previously mentioned, many-to-many relationships must be resolved before they can be implemented. An example of a many-to-many relationship that may exist in a karst database is the relationship between recharge features, such as swallets (insurgences), and discharge features (springs). A single swallet may feed multiple springs and multiple swallets may feed a single spring. To resolve this relationship a third table, called a resolving table, must be created. The primary keys from the recharge features table and the discharge features tables are copied to this new table (Figure 14). The primary key of the resolving table is the set of columns in the primary keys of both tables. Foreign key relationships should then be defined between the resolving table and both of its parents. Additional attributes may be created in this table. For example, if a contaminated spring is fed by two recharge points, only one of the recharge points may be contributing contaminants. Therefore, an attribute might be created to indicate which of the recharge features is contributing the contaminates.

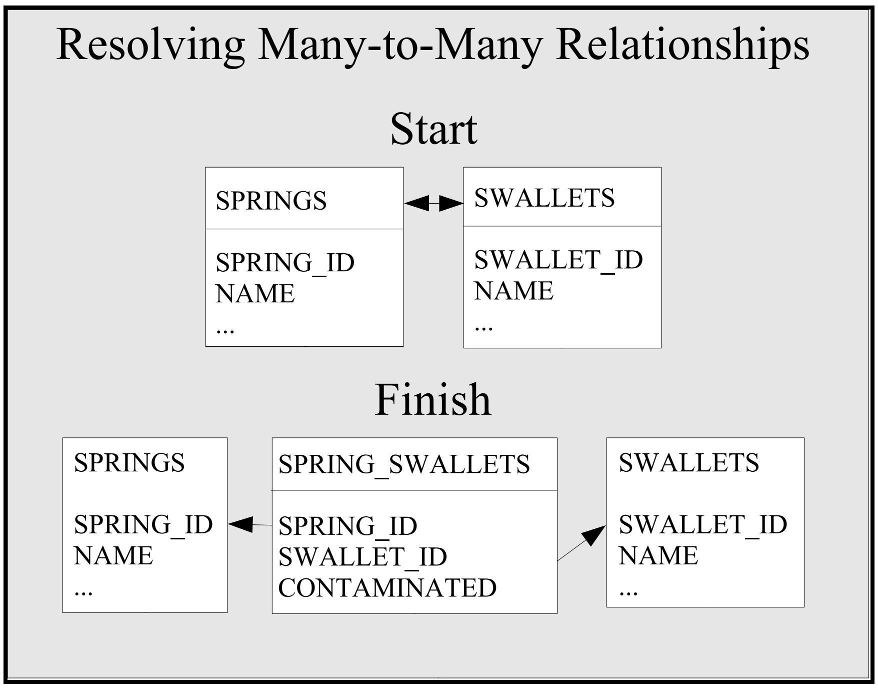


Figure 14: Process of resolving many-to-many relationships

In a well-designed relational database three rules are met: no repeating attributes; there are no redundant data; and the data in a table depend on the primary key. Repeating attributes occur when the same column appears multiple times within a table with slight differences in name. Redundant data occurs when the same data values occur multiple times within a column. If these three simple rules are followed, the resulting relational database will be in 3rd Normal Form, the “gold standard” for relational database design. Relational databases in 3rd Normal form are easier to maintain and will be less likely to contain incorrect or inconsistent data.

If, in the initial design, the CAVES table had ENTRANCE1, ENTRANCE2, and ENTRANCE3 as attributes, the CAVES table would have a repeating attribute, namely ENTRANCE. To eliminate repeating groups, move the offending attributes to a separate child table and store the repeated attribute as separate rows, as we had in the previous example (Figure 15).

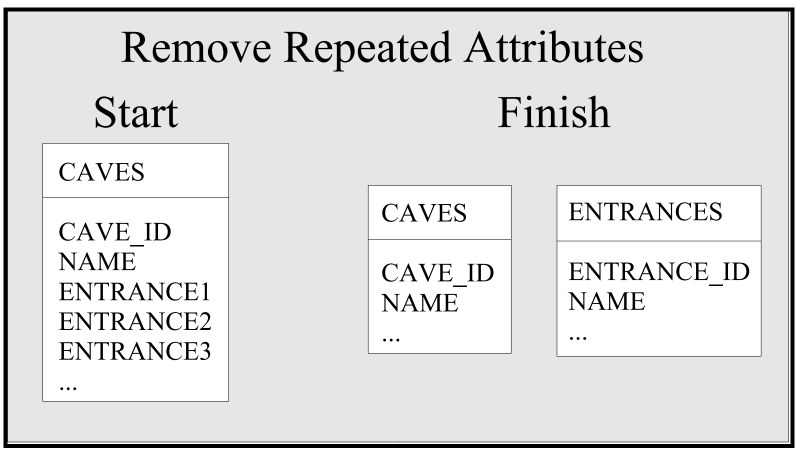


Figure 15: Process of eliminating repeated attributes from a table

Once repeating attributes are eliminated, look for redundant data. Redundant data are data that are repeated within an attribute of a table. Redundant data are acceptable and expected in foreign key attributes, but generally should be considered suspect in other columns. For example, if the RECHARGE_FEATURES table contained a SPRING_NAME column, the same spring might be duplicated for multiple recharge features. It would be best to create a separate table to hold the SPRING_NAME column and create a foreign key in the RECHARGE_FEATURES table to this new table (Figure 16).

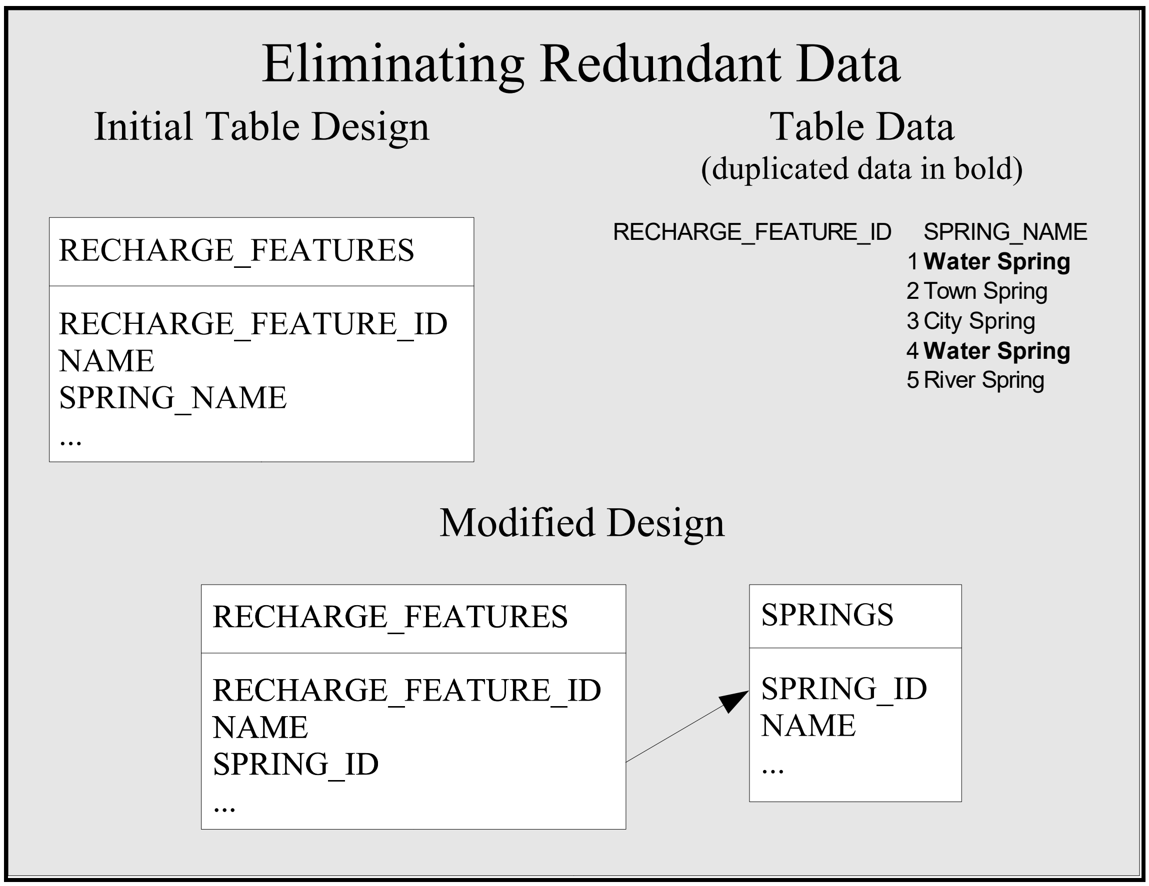


Figure 16: Process of eliminating redundant data

Finally, once redundant data are eliminated, or at least reduced, look for data that do not depend on the primary key. A latitude/longitude location is not dependent on the primary key of a cave. It is more appropriate to store such information for each entrance in a separate table, as a cave may be many kilometers in length and have several entrances while an entrance is more likely to be a geological point (Figure 17).

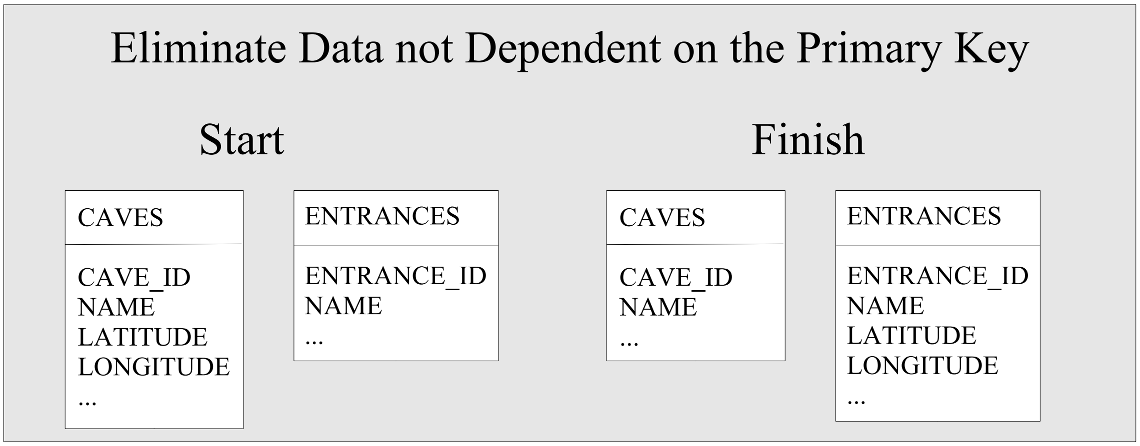


Figure 17: Eliminating data not dependent on the primary key

Relational databases are accessed by the SQL programming language. SQL, often pronounced “sequel”, stands for Structured Query Language. SQL consists of English-like commands that are interpreted by the target relational database management system (DBMS, or RDBMS for relational database management systems). SQL commands tell the RDBMS what to do, not how to do it and is therefore much simpler to use than other popular programming languages such as “C”, JAVA, or Visual Basic. There are separate SQL commands for creating, updating, deleting, and retrieving data. The overall syntax is what to do, what table(s), and attribute(s) to perform the operation against and what rows should be involved in the operation. For a complete description of the SQL language, see ANSI (1992). For example, the following SQL command retrieves the names and locations of all of the caves on Rota.

```
SELECT NAME, LATITUDE, LONGITUDE
FROM CAVES
WHERE ISLAND = 'Rota';
```

Many graphical tools have been developed that allow a user to access a relational database without having to know SQL commands. In addition, many RDBMS' provide such graphical interfaces.

A view is a stored SQL command. Views are used to reduce code redundancy and to hide complex SQL statements from the programmer or end user. Views, therefore, provide a simplified "window", or view, into the sometimes-complicated implementation of the database. A view can generally be operated on as if it were any other table in the relational database.

Indexes can be created to facilitate data access. Indexes are structures that store a sorted list of the contents of the indexed column, or columns, as well as a pointer back to the original data row. There are many search algorithms that allow a sorted list to be searched faster than an unsorted one and the specific algorithm used varies by RDBMS and is often hidden from the user. Indexes give the best retrieval response with a slight performance cost to data modification, creation, and deletion operations. In general, all primary and secondary keys are indexed as well as all foreign key columns and any other columns that are frequently searched.

CHAPTER VI

LITERATURE REVIEW

Karst GIS

Very little work has been done with GIS in relation to karst. An extensive literature review has revealed that the most sophisticated work has involved predicting sinkholes in a continental setting. Once a GIS database of known sinkholes was generated, the model used the distribution of sinkholes in order to classify the region into one of six relative hazard zones. This model was viewed as a success where the location of sinkholes had been accurately mapped and the density of sinkholes was fairly high (Gao, 2002, 2004). Gao (2004) used lineament, nearest neighbor, decision tree, and cartographic analysis to delineate the hazard zones.

Typically, GIS has been used simply as a centralized repository of cave and karst data for a specific region. Cave locations and maps, survey data, field observations, list of unexplored areas of the cave, and other data have been stored in GIS databases (Addison, 2003; Iliffe, 2003). A GIS database can be used to identify gross errors in field notes and to produce better maps (McKenzie and Veni, 2003), especially when data are entered directly into a GIS system, the use of GIS software can improve cave maps by reducing the errors that occur when data is copied a number of times and to help identify gross errors in the survey.

Alternatively, a descriptive GIS of known caves can be used to identify where a cave resource is likely to be found. If a cave's entrance location is known and the location and size of cave passages is known, overlaying the cave map with the overlying topography can tell you where the cave nearly intersects the surface. This information can then be used to identify places where additional fieldwork should be performed to potentially find additional cave resources (McKenzi and Veni, 2003). Knowing where to focus exploration can greatly increase an explorer's probability of finding previously unknown caves. One team used GIS to map known cave and karst features in order to identify patterns in and distribution of karst features (Lyew-Ayee et al., 2003). Mylroie et al (2005) produced a digital karst map of the known cave and karst features of Mississippi. ArcGIS was used to produce maps of Mississippi that highlighted counties with known caves, and to produce all of the maps in the digital karst map. The final product was published as a series of hyperlinked html pages on a CDROM.

In addition to maps of cave features, GIS has been used for the mapping of karst features including karst-prone geology, and specific karst features such as sinkholes and karst drainage basins. Paylor et al. (2003) used GIS to map the karst prone geology and sinkholes of Kentucky. This statewide map can then be used by the public and both public and private organizations to identify potential environmental and developmental issues. In addition to using GIS to map sub-surface features, GIS has been used to map surficial karst features and, sometimes, their connection with sub-surface features. One such project is the Florida Cave Database. The National Speleological Society Cave

Diving Section and others that map underwater cave passages provided subsurface data for this project. Included in the database are fields such as ownership, entrance locations, conduit size and trend, and direction of water flow. After the data were acquired, an attempt was made to correlate the sub-surface features with known sinkholes and other surficial karst features (Denizman, 2004).

There are significant issues in mapping the flow of water through karst systems because the flow of groundwater in karst aquifers differs from traditional aquifers in that the speed, direction, and distance of water travel are quite different. Subsurface waters may flow for many kilometers at rates comparable to that of surface streams and may cross under surface divides. Glennon (2003) used GIS to develop a model to better understand and predict the flow of groundwater in karst aquifers. If such a general model can be produced, it can be applied to the efforts of many, including Lindsay and Smart (2004) who used GIS to map karst groundwater flow to map potential contamination risks in a karst area.

Lindsay and Smart (2004) used a GIS to map the level of the water table and to identify underground watersheds in terms of quality, quantity, flow directions, divides and conduits. Part of the reason for the mapping of karst groundwater is to map potential contamination risks (Lindsay and Smart, 2004; Singhal and Samuelson, 2004). Other uses for karst aquifer mapping are for governmental planning (Paylor et al., 2003), freeway route selection (Florea and Gulley, 2004; Griffin and Florea, 2004), and creating management zones to redirect urban development (Veni, 2004).

Proper planning of development in karst regions not only reduces the environmental impact of the human activities, but it can also be used to help guide development activities. One of the major issues facing planners in karst areas is the high risk of groundwater contamination due to potential of rapid and unfiltered transport of contaminated water to unknown destinations. In addition to the work done by Paylor et al. (2003), and other researchers such as Kostka et al. (2004) have used GIS maps to help governments to create development plans and change zoning to better reduce the risk of future groundwater contamination.

Remote Sensing

LANDSAT Data

LANDSAT satellites are a series of satellites, first launched in 1972 that produce remotely sensed images of the Earth's surface. The only two LANDSAT satellites currently functioning are LANDSAT-5 (launched in March 1984), and LANDSAT-7 (launched in April 1999). LANDSAT-5 has a primary sensor called the Thematic Mapper (TM) and LANDSAT-7's is called the Enhanced Thematic Mapper Plus (ETM+) (USGS, 2005b).

LANDSAT-5's TM sensor has a resolution between 30 and 120 m. The seven spectral bands have a resolution of 30 meters (Table 2); the thermal infrared band has a resolution of 120 m that is resample to 30 m (USGS, 2005b).

Table 2: LANDSAT-5 TM Sensor Information (USGS, 2005a)

Band	Wavelength (Micrometers µm)	Color	Resolution
Band 1	0.45-0.52 µm	Blue	30 m
Band 2	0.52-0.60 µm	Green	30 m
Band 3	0.63-0.69 µm	Red	30 m
Band 4	0.76-0.90 µm	Near Infrared	30 m
Band 5	1.55-1.75 µm	Mid-Infrared	30 m
Band 6	10.40-12.50 µm	Thermal-Infrared	120 m
Band 7	2.08-2.35 µm	Mid-Infrared	30 m

LANDSAT-7's ETM+ sensor is a high-resolution sensor with nominal spatial resolution between 15 and 60 m. The panchromatic band has a resolution of 15 m, the thermal infrared band has a resolution of 50 m, and the remaining six bands have a resolution of 30 m. Table 3 summarizes the information provided by the ETM+ sensor (USGS, 2005b). On May 31, 2003 LANDSAT-7's started experiencing a problem with its scan line corrector (SLC) and is no longer completely functional (USGS, 2005c). Data from LANDSAT-7 after May 31, 2003 is processed to fill in the gaps in the data caused by the SLC problem. The gaps in the LANDSAT-7 data are filled by an interpolation of the missing data (USGS, 2005d).

Table 3: LANDSAT-7 ETM+ Sensor Information (USGS, 2005a)

Band	Wavelength (Micrometers µm)	Color	Resolution
Band 1	0.45-0.52 µm	Blue	30 m
Band 2	0.53-0.61 µm	Green	30 m
Band 3	0.63-0.69 µm	Red	30 m
Band 4	0.78-0.90 µm	Near Infrared	30 m
Band 5	1.55-1.75 µm	Mid-Infrared	30 m
Band 6	10.40-12.50 µm	Thermal-Infrared	60 m
Band 7	2.09-2.35 µm	Mid-Infrared	30 m
Band 8	0.52-0.90 µm	Multispectral	15 m

Remotely Sensing Geology

Abdullah and Mat Akhir (1997) attempted to use LANDSAT images to determine vegetative cover as a predictor of the geology and the underlying geology of the Langkawi Islands, Malaysia. They found that when various color bands were used the lithological units were clearly visible. Limestone units showed as a light blue-green color in the TM 432 color composite image, granitic units showed as a deep red color in the same composite, the Machinchang Formation (sandstones, conglomerate and greywacke) showed as a red color, the Singa Formation of sandstones, siltstones, and mudstones showed as spotted blue and pink, alluvium displayed as dark red and the Chuping Formation (limestone) showed as reds and pinks with light-blue mottles.

Laes et al (unpublished) used LANDSAT TM data to map acid mine drainage in the Howard Fork Drainage Basin of Colorado. By assigning different band ratios to the red, green, and blue colors, they found that LANDSAT TM data could be used to identify broad mineral groups, but not individual minerals. In their study they assigned the ratio of band 3 to band 1 (B3/B1) to blue, the ratio of band 5 to band 4 (B5/B4) to green, and the ratio of band 5 to band 7 (B5/B7) to red. Clays, carbonates, sulfates, and vegetation show as reds, ferric minerals (Fe^{3+}) show as blues, and ferrous minerals (Fe^{2+}) show as greens. Vegetation was pulled out of the B5/B7 ratio by masking all pixels with NDVI values greater than 0.2.

Remotely Sensing Vegetation

Band ratioing is a technique where a ratio of two bands is taken to emphasize feature reflectance differences between the two bands. One of first band ratios to be used was the vegetation index (VI), developed by Birth and McVay (1968). This first VI is a simple ratio of the near infrared (NIR, LANDSAT band 4) to red (LANDSAT band 3) (Equation 6-1).

$$SR = \left(\frac{NIR}{Red}\right) \tag{6-1}$$

where:

SR	=	Simple Ratio
NIR	=	Near infrared band, LANDSAT band 4
Red	=	Red band, LANDSAT band 3

The problem with the Birth and McVay simple ratio is that the results are unbounded; meaning that there is no fixed range to the results. Second, negative values are possible. For these reasons Rouse et al (1974) developed the Normalized Difference Vegetation Index (NDVI) (Equation 6-2).

$$\text{NDVI} = \left(\frac{\text{NIR} - \text{Red}}{\text{NIR} + \text{Red}}\right) \quad (6\text{-}2)$$

where:

NDVI	=	Normalized Difference Vegetation Index
NIR	=	Near infrared band, LANDSAT band 4
Red	=	Red band, LANDSAT band 3

According to ABM (2005) clouds and water typically have NDVI values less than zero, rock, and bare soil around zero, and vegetation has values from 0.1 to 0.6, depending on vegetation type and density. NDVI values that show vegetation are further divided. Values between 0.1 and 0.2 represent shrub and grassland; values between 0.2 and 0.6 are mixed forests and values higher than 0.6 indicate temperate and tropical rainforests (NEO, 2005).

Goward et al (1991) found that the results of the NDVI are often significantly in error because of changing soil and atmospheric conditions. Huete and Justice (1999) identified the need to develop a VI that did not need field calibration for every vegetation region and also remained constant under changing soil and atmospheric conditions. Their Enhanced Vegetation Index (EVI) (Equation 6-3) takes both of these variables into account.

$$\text{EVI} = \left(\frac{p^*_{nir} - p^*_{red}}{p^*_{nir} + C_1 p^*_{red} - C_2 p^*_{blue} + L} \right)(1 + L) \tag{6-3}$$

where:

EVI	=	Enhanced Vegetation Index
P^*_{nir}	=	Near infrared band corrected for molecular scattering and ozone absorption
P^*_{red}	=	Red band corrected for molecular scattering and ozone Absorption
P^*_{blue}	=	Blue band corrected for molecular scattering and ozone absorption
C_1	=	Constant empirically determined to be 6.0
C_2	=	Constant empirically determined to be 7.5
L	=	An adjustment factor empirically determined to be 1.0

The red and near-infrared bands are used in vegetation indicies because most leaves absorb a significant portion of the red band for photosynthesis but reflect most of the near-IR band. Plant leaves reflect the near-IR band because absorption of near-IR radiation would cause the plant leaves to become hot enough to effect the proteins in the plant's cells. Some of the near-IR radiation that hits a plant leaf is reflected and the rest is transmitted through the leaves and is reflected back by the leaves below it. Therefore, a denser canopy will reflect a greater percentage of the near-IR radiation than will a less dense canopy. Because of the absorption and reflective properties of plant leaves in the red and near-IR bands, respectively, there is a direct relationship between the near-IR band and plant biomass and an inverse relationship between the red band and plant biomass. The more dense the vegetation, the less red and more near-IR energy will be reflected (Jenson, 2000).

CHAPTER VII

METHODS AND RESULTS

Database Development

A relational geodatabase (GDB) in 3NF was developed in Microsoft Access (Microsoft, 2000a) to store spatial and non-spatial information for each of the cave and karst features in the descriptive GIS. The tables in this database are: ACCURACY_INFORMATION, CAVE_TYPES, CAVES, HYDRAULIC_FUNCTION, ISLANDS, PROVINCES, and SURVEY_GRADE. The ACCURACY_INFORMATION table contains the accuracy of the location information an information as to how the location of the cave or karst feature was obtained; CAVE_TYPES contains information as to the karst feature type (e.g., Flank Margin Cave, Closed Depression, etc.); HYDRAULIC_FUNCTION stores information on whether the feature serves to recharge the groundwater or if the feature is discharging groundwater, and optionally, at what rate; ISLANDS contains information specific to each island; PROVINCES contains information on the physiographic provinces; SURVEY_GRADE contains information as to the accuracy of the survey performed on the karst feature; and CAVES holds the information on the caves and karst features for the islands including the location information.

Each table has a surrogate (artificial) key as its primary key. Foreign keys to ACCURACY_INFORMATION, CAVE_TYPES, PROVINCES, and

SURVEY_GRADE were created in the CAVES table and a foreign key to ISLANDS was created in the PROVINCES table.

To speed retrieval, individual indexes were created on each of the primary and foreign keys as well as each of the name columns. The database design is shown in Figure 18. To speed retrieval, indexes were created on all of the name columns as well as on the primary and foreign key columns.

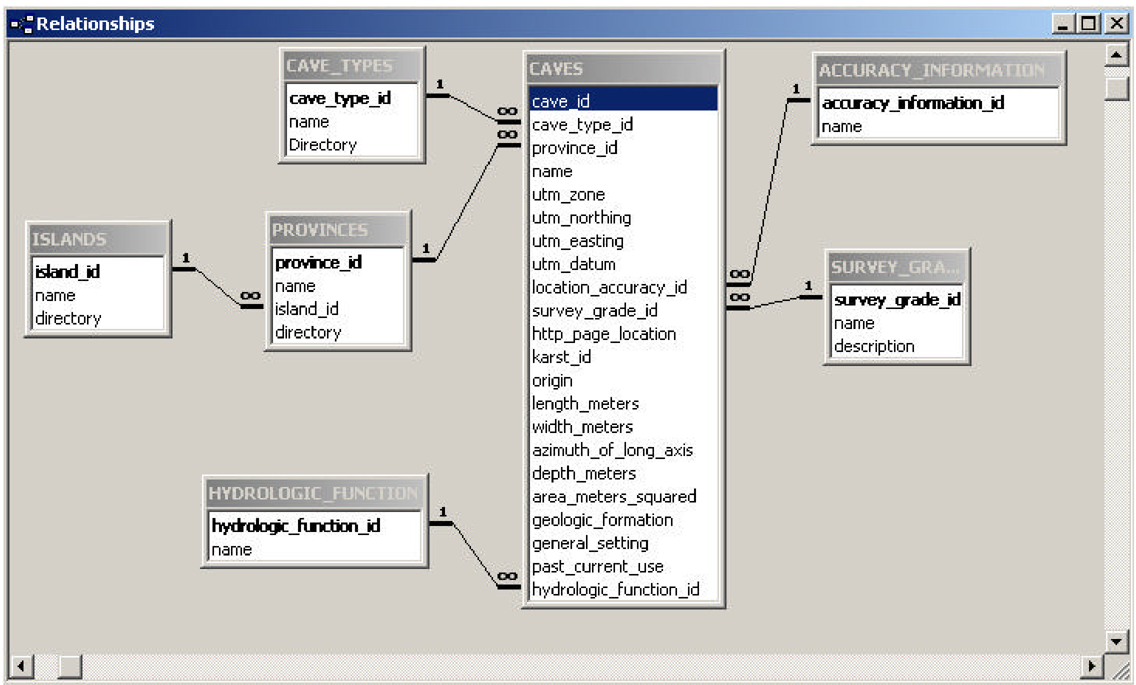


Figure 18: Geodatabase design including tables, columns, and relationships

Data Collection and Processing

The data for this project has already been collected for various projects, including various Masters Theses by Mississippi State University and University of Guam students.

The descriptive database was created using a combination of ESRI's ArcGIS 9.1 (ESRI, 2005) and Erdas Imagine 8.6 (Leica, 2002) GIS packages. Various components of the ArcGIS package were used including ArcMap, ArcCatalog, ArcToolbox, Spatial Analyst, and Publisher.

The data included in the descriptive GIS were received in various formats. The working cave maps were received in XaraX (Xara, 1997), the final cave maps are in either BMP or JPEG format, reduced line plot data in either Compass (FountainWare, 2005) or Walls (McKenzie, 2002) format, cave descriptions were received in either Microsoft Word (Microsoft, 2000d) or Adobe PDF (Adobe, 2005) format, karst features lists were received in either Microsoft Excel format (Microsoft, 2000b) or Adobe PDF format, GIS data was received in ArcGIS's shapefile format, Digital Elevation Models (DEMs) were received in Spatial Data Transfer Standard (SDTS) format, Digital Raster Graphics were received in TIFF format, and the LANDSAT images were received as multiple TIFF files, one for each band.

The DEMs were converted to ArcGIS GRID format using the sdts2grid (Townsend, 2002) program because ArcGIS and Erdas Imagine do not correctly convert SDTS files.

All of the digital data (maps, HTML pages, etc.) mentioned in this section are available on a case-by-case basis. See the conclusions for contact information.

Rota

Keel (2005) developed a preliminary GIS of the cave and karst features of Rota as part of the requirements for his Masters of Science degree from the Mississippi State University Department of Geosciences. It contains general locations and descriptions of the mapped karst features of Rota broken down by cave type and physiographic province. The reduced survey data in Walls format, with location information; working cave maps in XaraX format; and final cave maps in JPEG format were received via personal communication with Keel.

Once acquired, the data were initially split into directories, one for each cave. During the initial data organization it was found that five caves (Comet Cave, Cupid Cave, Even Smaller Cave, Prancer Cave, and Vixen Cave) were missing location data, three caves were missing XaraX map source files (*Alaguan* Cave, *Al-Su* Cave, and Even Smaller Cave), four caves were missing Walls data (Discus Cave, Rota Rooter Cave, Even Smaller Cave, and *Alaguan* Cave), three caves were missing descriptions (Jug Handle Cave, Even Smaller Cave, and Mermaid Cave), and two caves were missing completed maps (Even Smaller Cave and Mermaid Cave). Approximate location data for Comet, Cupid, Prancer, and Vixen Caves was obtained via a personal conversation with Keel. Some research had to be performed in order to correctly perform this initial organization as many of the caves were named differently in each source.

After the data were organized into separate directories for each cave, a vetting process took place to correctly identify each cave's type and physiographic province. The location data retrieved from the Walls files and the descriptions were used to vet the physiographic province information, and the cave maps and descriptions were used to vet the cave types. Table 4 summarizes the changes that were made from Keel's thesis. The organized data for Rota are summarized in Appendix C.

Table 4: Province and Cave Type changes from Keel (2005)

Cave Name	Original Province	Corrected Province	Original Cave Type	Corrected Cave Type
Alaguan Bay Cave			Mixing-zone Fracture	Flank Margin
Bare Foot Cave			Sea Cave	Flank Margin
Bee Cave	Sabana	Taipingot	Flank Margin	Mixing-zone Fracture
Big Fern Cave	Sinapolo	Sabana		
Breccia Cave			Other	Flank Margin
Canyon Cave			Other	Sea Cave
Compact Cave	Sabana	Sinapolo	Other	Flank Margin
Even Smaller Cave	Sinapolo	Sabana	Other	Flank Margin
Fall-In Cave			Other	Fissure
Gagani Cave			Fault	Contact
Hang Out Cave	Sinapolo	Sabana	Flank Margin	Mixing-zone Fracture
Henry Fissure Cave	Sinapolo	Sabana		
Honey Eater Cave			Flank Margin	Mixing-zone Fracture
Husky Cave	Sinapolo	Sabana		
Jug Handle Cave		Sabana		Fissure
Kaigun 223 Japanese Command Post			Sea	Man-made
Liyang Chenchon	Sinapolo	Sabana		
Liyang Tonga				Mixing-zone Fracture
Paupau Sea Cave	Sabana	Taipingot		
Prancer Cave	Sinapolo	Sabana		
Sea Stack Cave	Sinapolo	Sabana		
Slab Cave			Other	Fissure
Vixen Cave	Sinapolo	Sabana		
Water Cave			Flank Margin / Contact	Flank Margin

After the data were vetted, a directory was created for the island, subdirectories were created for each physiographic province, and further subdirectories were created for each cave type. Then the cave directories were moved to the correct cave type subdirectory.

When the data were organized a series of HTML pages was created, one for each feature. The HTML page was created in the directory for the feature. The HTML pages contain the cave descriptions and cave maps from Keel (2005) as well as links to the Walls line plots and the XaraX working map files, if available.

The data were then loaded into a Microsoft Excel spreadsheet for easy manipulation. Once basic cleaning of the data had occurred, the data were then loaded into the Microsoft Access GDB using the import table command. The http_page_location field was then updated to the correct directory name using a SQL update statement. Once the data were in the GDB and fully populated, one layer file was created for each combination of cave type and physiographic province that exists in the GDB. The layer files were created in ArcCatalog and use a SQL query to pull information on the appropriate cave or karst features from the GDB. These layer files were then loaded into an ArcMap document for Rota. Once in ArcMap, the display properties were modified to support hyperlinks based on the http_page_location field in the CAVES table, and the label properties were modified to label each feature using the name field in the CAVES table. Finally the symbology was changed to use a different symbol for each physiographic province and a different color for each cave type within physiographic province (Figure 19).

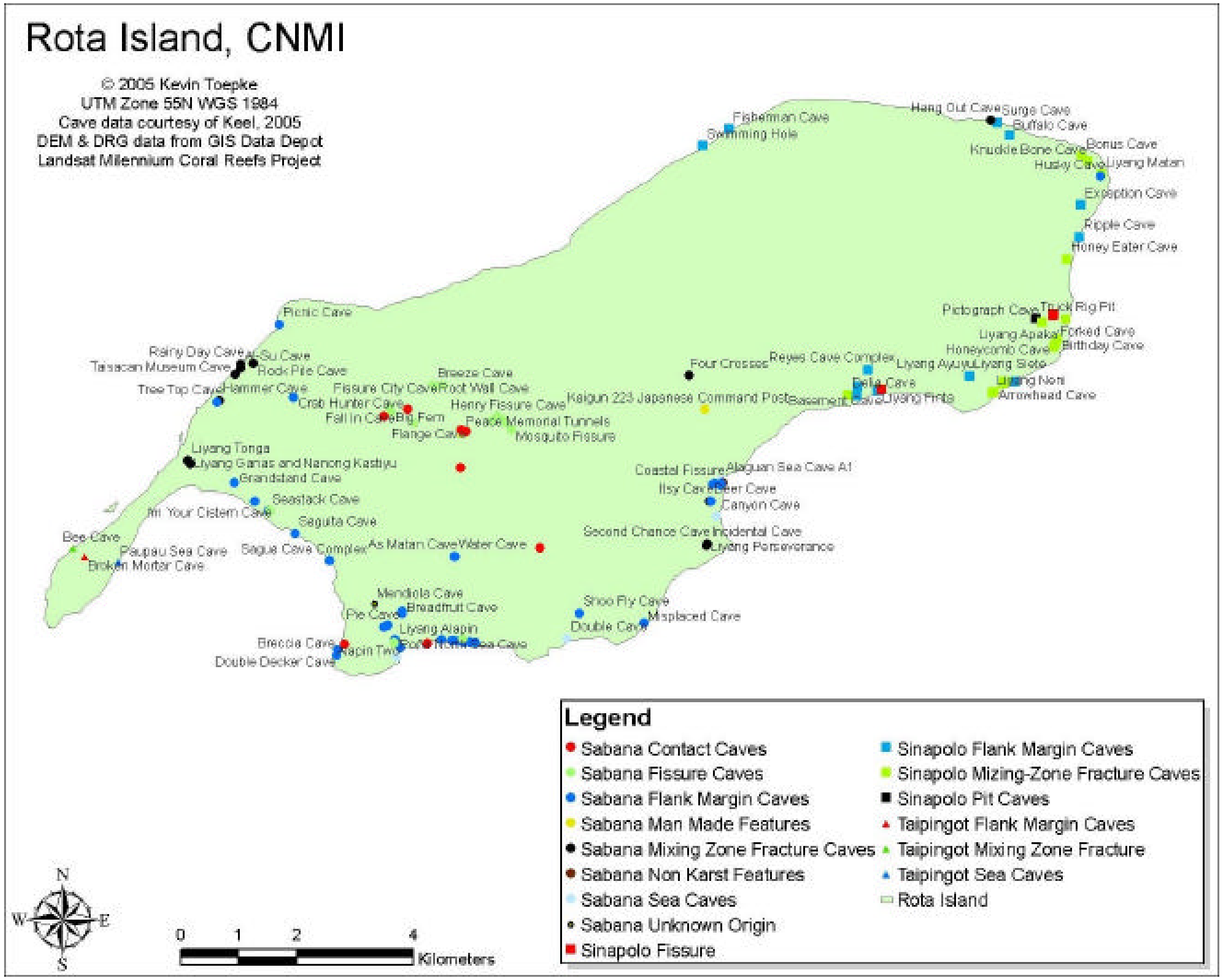


Figure 19: Map of Rota with Cave Layers and Island Outline

The preliminary GIS produced by Keel had many additional layers of interest to karst researchers including: Water Cave catchment estimates, firm and estimated volcanic contacts, roads and rivers in the *Sabana* Region. These layers were imported into the GDB using ArcCatalog's Import Feature Class (single) function then added to the map of Rota (Table 5, Figure 20).

Table 5: Layers from Keel's GIS that were added to the GDB

Layer Filename	Layer Type	Contents	GDB Feature Name
As Mundo Fissure Zone	Line	Rough outline of the *As Mundo* Fissure Zone	RotaAsMundoFissureZone
Firm Contact	Line	Firm volcanic contact at the top of the *Sabana*	RotaSabanaContactFirm
Fissure City	Line	Rough outline of the Fissure City area	RotaFissureCity
Indefinite Contact	Line	Estimated volcanic contact at the top of the *Sabana*	RotaSabanaContactEstimated
Liberal Water Cave Catchment	Polygon	Liberal estimate of the catchment area for Water Cave	RotaWaterCaveCatchmentLiberal
Moderate Water Cave Catchment	Polygon	Moderate estimate of the catchment area for Water Cave	RotaWaterCaveCatchmentModerate
North Side Contact Estimated	Line	Estimated volcanic contact at the north side of the *Sabana*	RotaNorthSideContactEstimate
North Side Contact Firm	Line	Firm volcanic contact at the north side of the *Sabana* region	RotaNorthSideContactFirm

Table 5 (Continued)

Layer Filename	Layer Type	Contents	GDB Feature Name
Sabana Diffuse Recharge	Point	Diffuse recharge points on the Sabana	RotaSabanaDiffuseRecharge
Sabana insurgences	Point	Insurgences on the Sabana	RotaSabanaInsurgences
Sabana Rivers	Line	Rivers on the Sabana	RotaSabanaRivers
Sabana Roads	Line	Roads on the Sabana	RotaSabanaRoads
Talakaya Contact	Line	Volcanic contact at the top of the Talakaya region	RotaTalakayaContact
Water Cave Catchment Conservative	Polygon	Conservative estimate of the catchment area for Water Cave	RotaWaterCaveCatchmentConservative
XY Palii Contact	Point	Coordinates of volcanic outcrops near Palii	RotaPaliiVolcanicOutcrops
XY Talakaya Contacts	Point	Coordinates of volcanic outcrops in the Takalaya region	RotaTalakayaContacts
XY Volc Outcrops	Point	Coordinates of volcanic outcrops	RotaVolcanicOutcrops

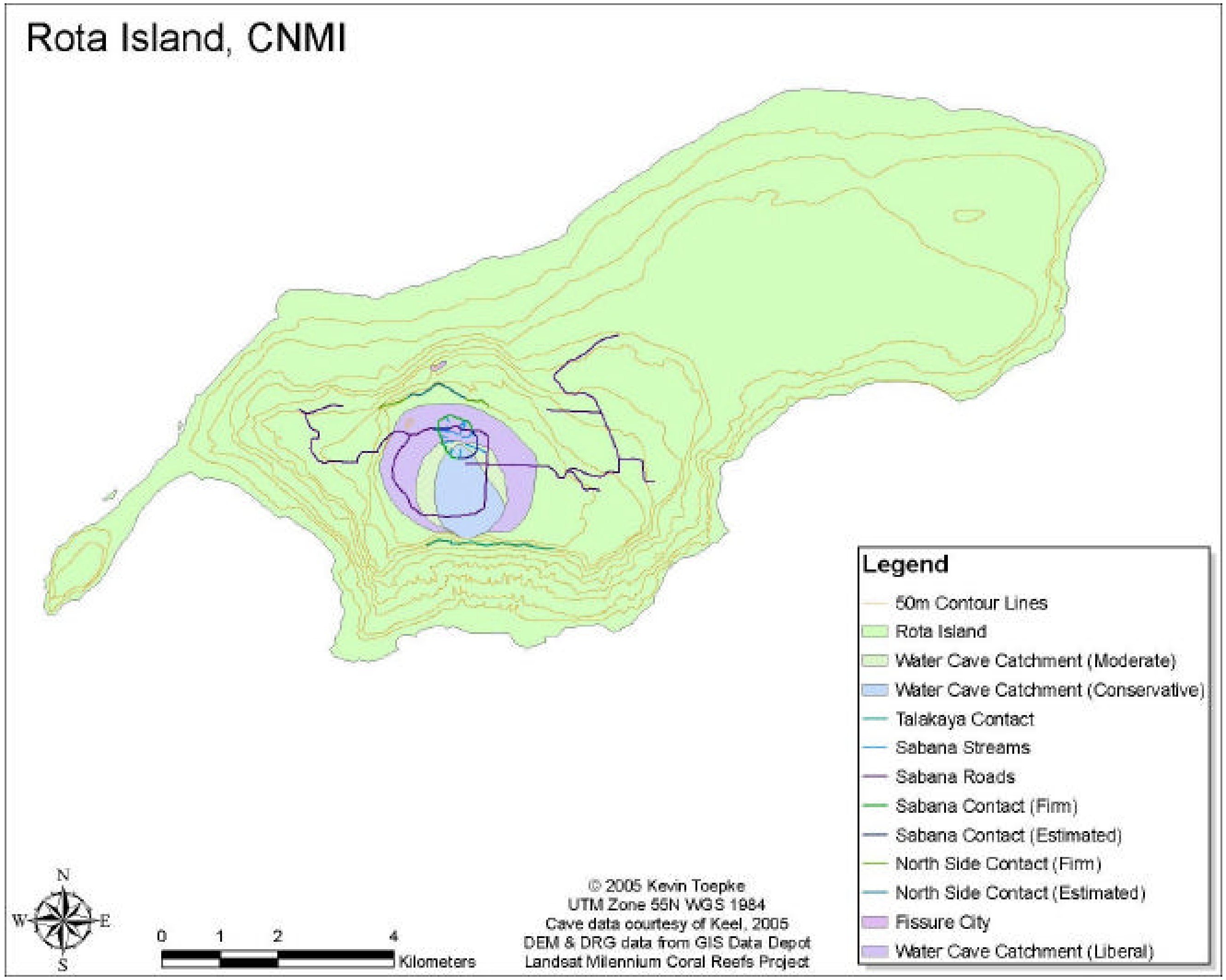


Figure 20: Map of Rota showing layers imported from Keel's GIS

The LANDSAT-7 scene that covers Rota is Path 100, Row 50. The Millennium Coral Reef Project had scenes from two dates, 08/17/1999 (NASA, 2005c) and 03/15/2001 (NASA, 2005d), both scenes had less than 25% total cloud cover. Erdas Imagine was used to stack the multiple source image files into multi-layer image files, one for each date. Once complete, both of the scenes were subsetted using a rectangular area of interest in Erdas Imagine to include just a small area around the island of Rota. The subsetted 08/17/1999 scene was twice loaded into the ArcMap document (Figures 21 & 22). The symbology on one of the scenes was changed to true-color (Band-1 to blue, Band-2 to green, Band-3 to red), and the other had its symbology changed to false-color IR (Band-2 to blue, Band-3 to green, Band-4 to red).

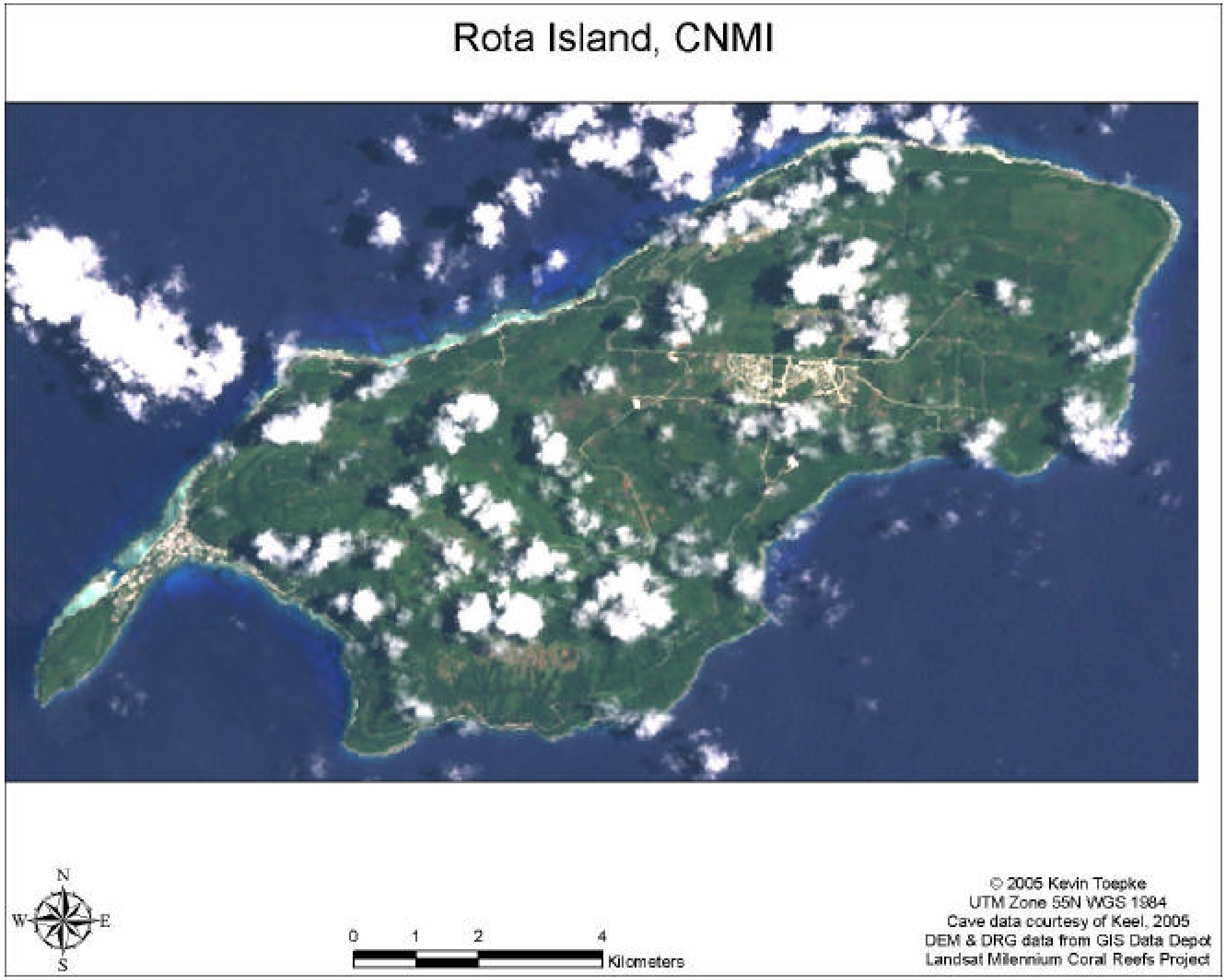


Figure 21: True Color LANDSAT-7 Image of Rota Island

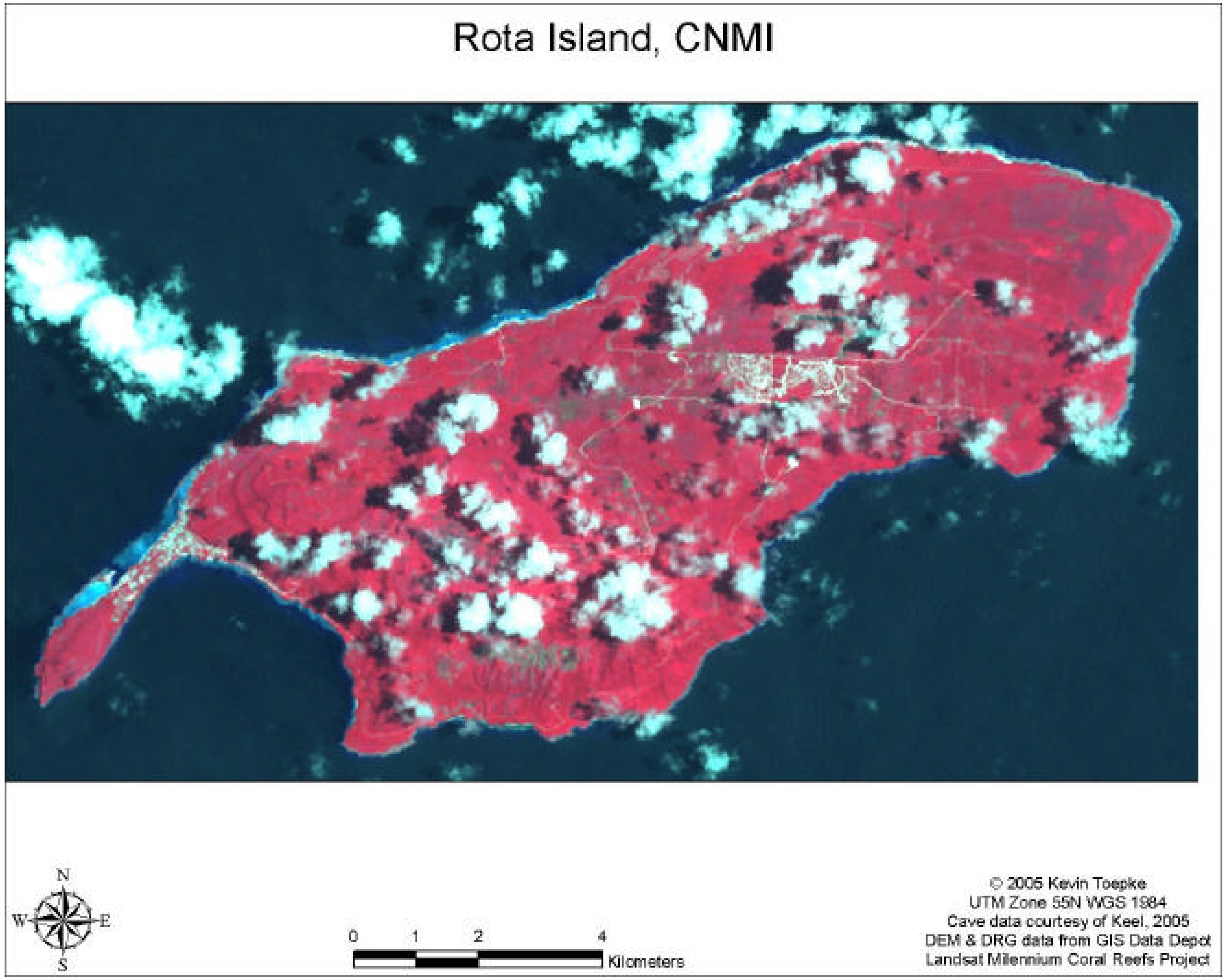


Figure 22: False Color IR LANDSAT-7 Image of Rota Island

Digital Elevation Models (DEMs) for Rota in the SDTS format were acquired from USGS (2001b and 2001c). These DEMs were converted into GRID format using sdts2grid, and merged using ArcGIS grid command. After reprojecting the merged DEM to WGS 1984 UTM Zone 55N, the merged DEM were then loaded into the ArcMap document for Rota (Figure 23). Upon loading the merged DEM into ArcMap, it was found that the DEM also needed to be georectified to the LANDSAT image. This was done using the Reference option in the Georeference toolbar in ArcMap. The LANDSAT image was chosen as truth because it more accurately lined up with the cave locations than the DEM.

Once the DEM was georectified the following computations were made on the DEM in Spatial Analyst: hillshade document (Figure 24) 10-m contour lines (Figure 25), 25-m contour lines (Figure 26), and 50-m contour lines (Figure 27). The contour lines were computed by using the contour option within Spatial Analyst, hillshade using the Hillshade option, and island outline was computed by using Raster Calculator to set all elevations less than or equal to zero to zero and all elevations greater than zero to one then converting the resulting grid data to a polygon using the Export Raster to Feature option in Spatial Analyst. Once the contour and island outline calculations were complete, the results were imported into the geodatabase using ArcCatalog's Import Feature Class (single) command. The resulting feature classes were then added to the ArcMap for Rota and the symbology was changed to contour for the contour lines and a fill-color of green for the Island Outline.

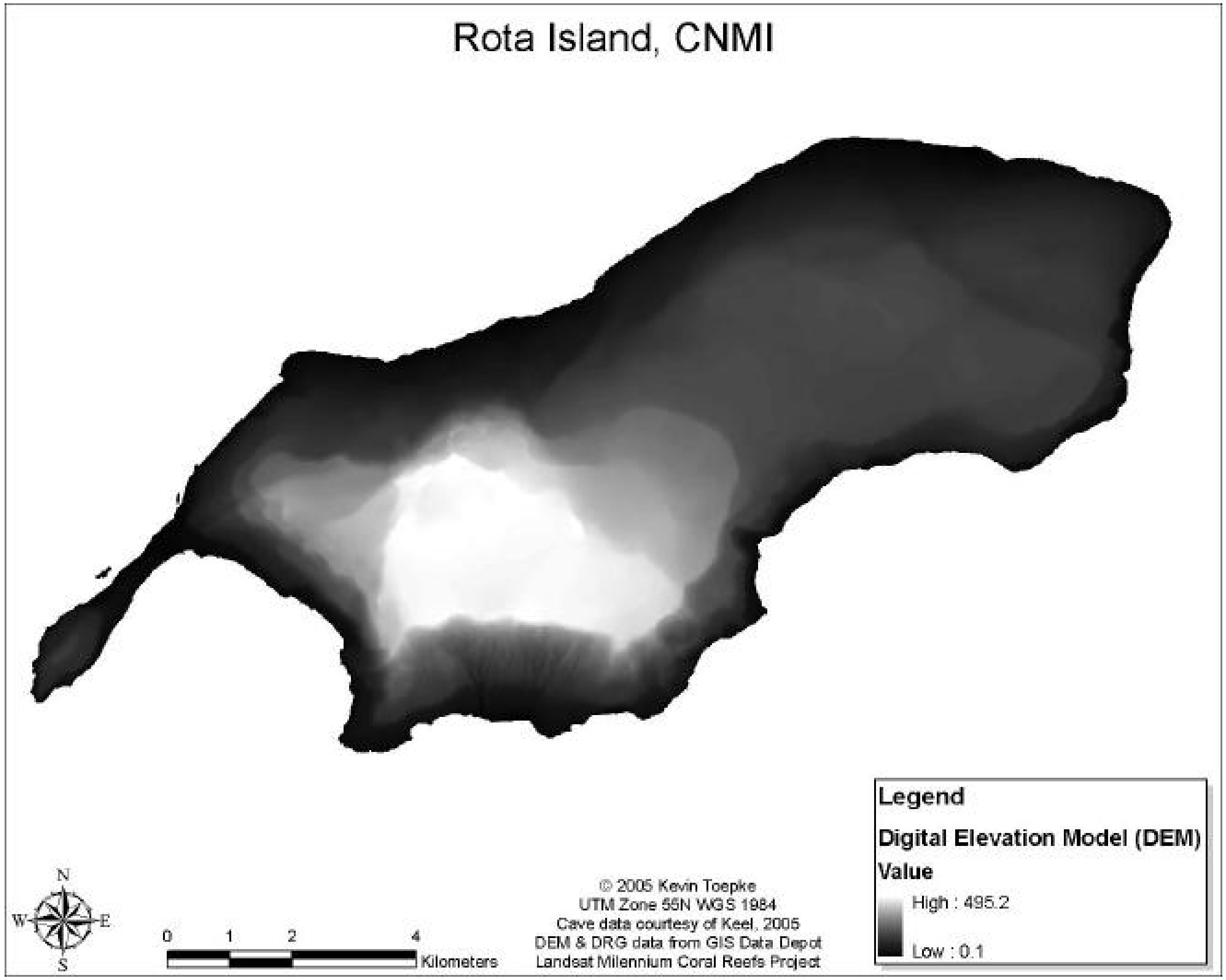


Figure 23: Digital Elevation Model (DEM) of Rota Island

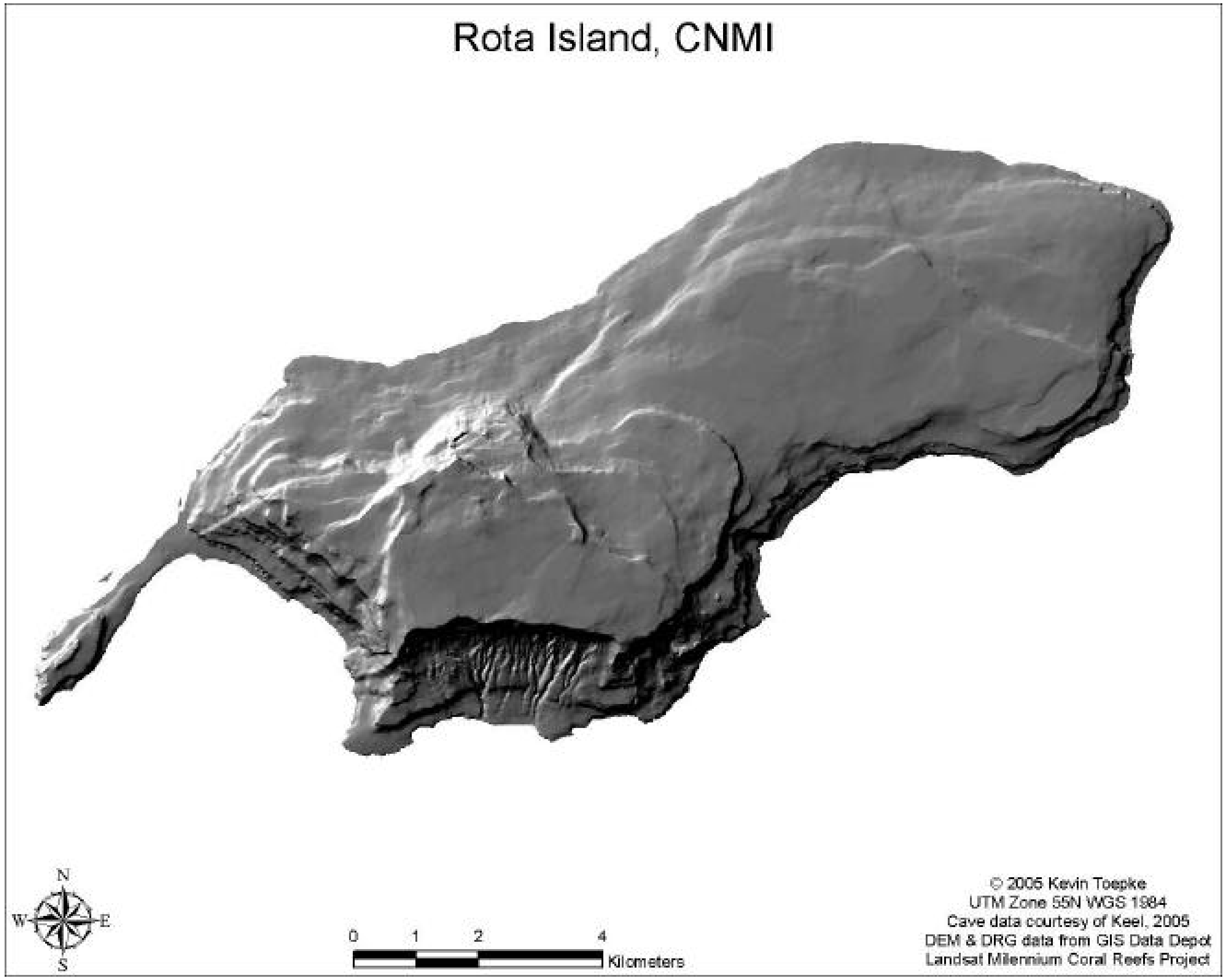


Figure 24: Hillshade of Rota generated from the DEM of Rota Island

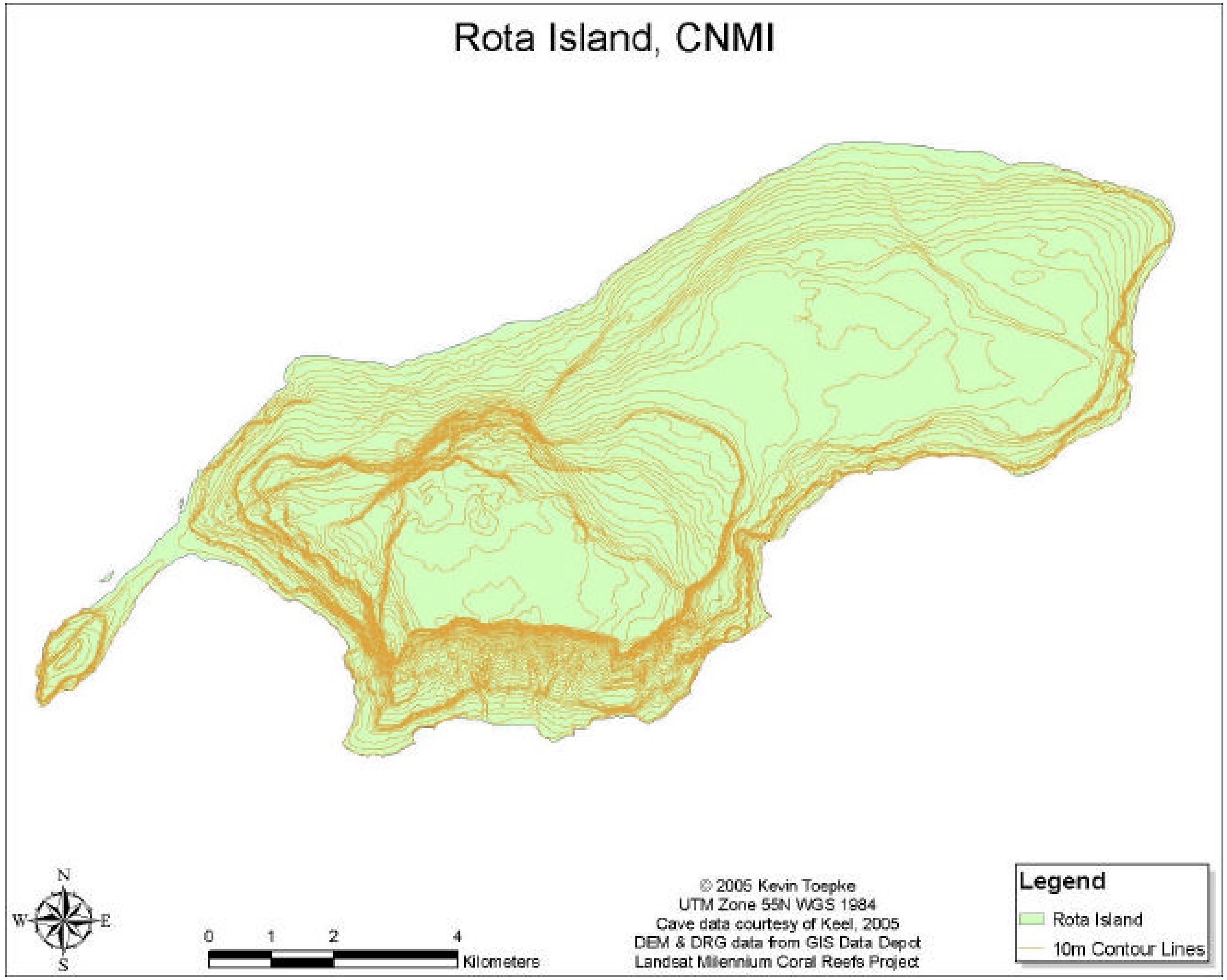


Figure 25: Map of Rota Island with island outline and 10m contour lines generated from the DEM of Rota Island

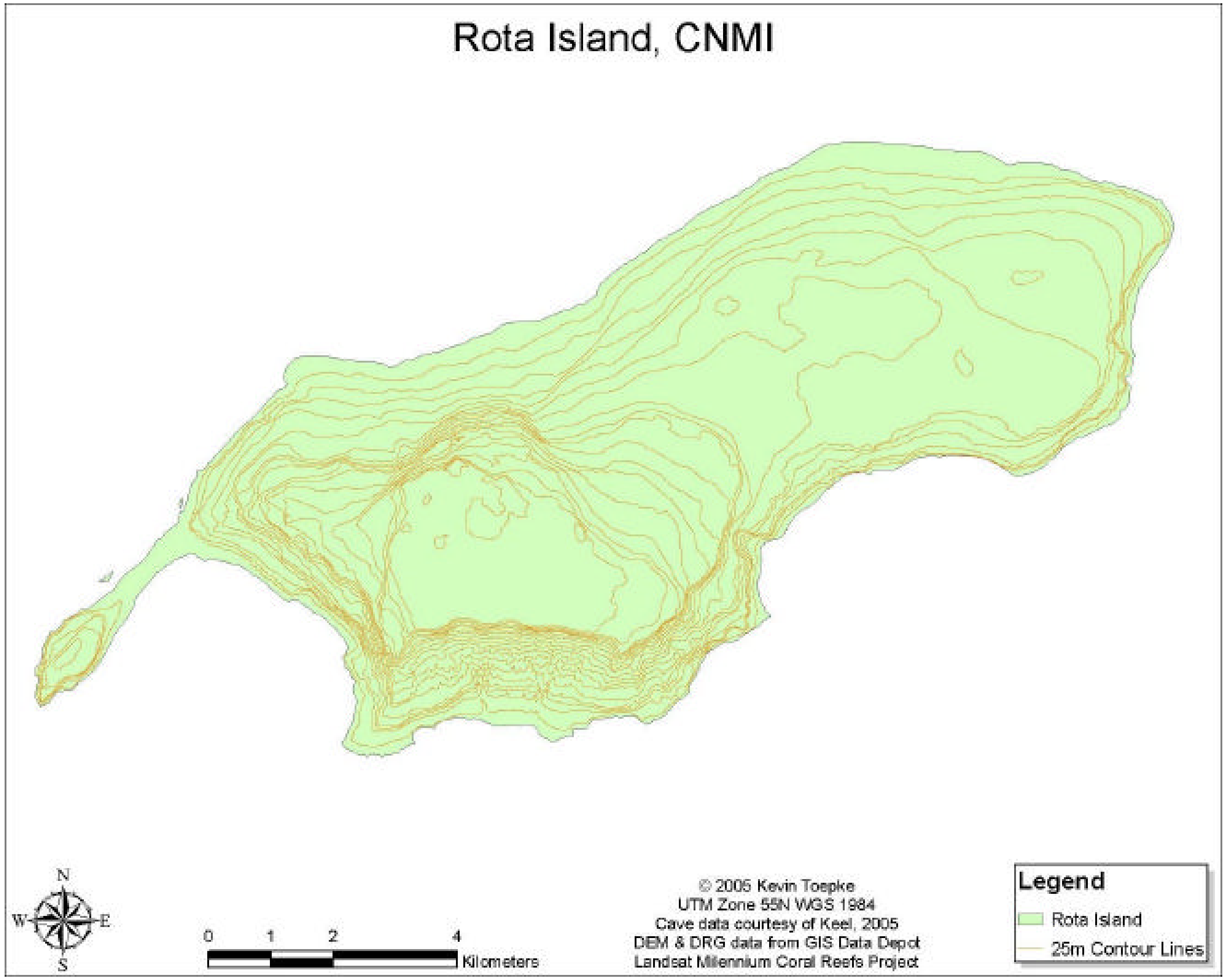


Figure 26: Map of Rota Island with island outline and 25m contour lines generated from the DEM of Rota Island

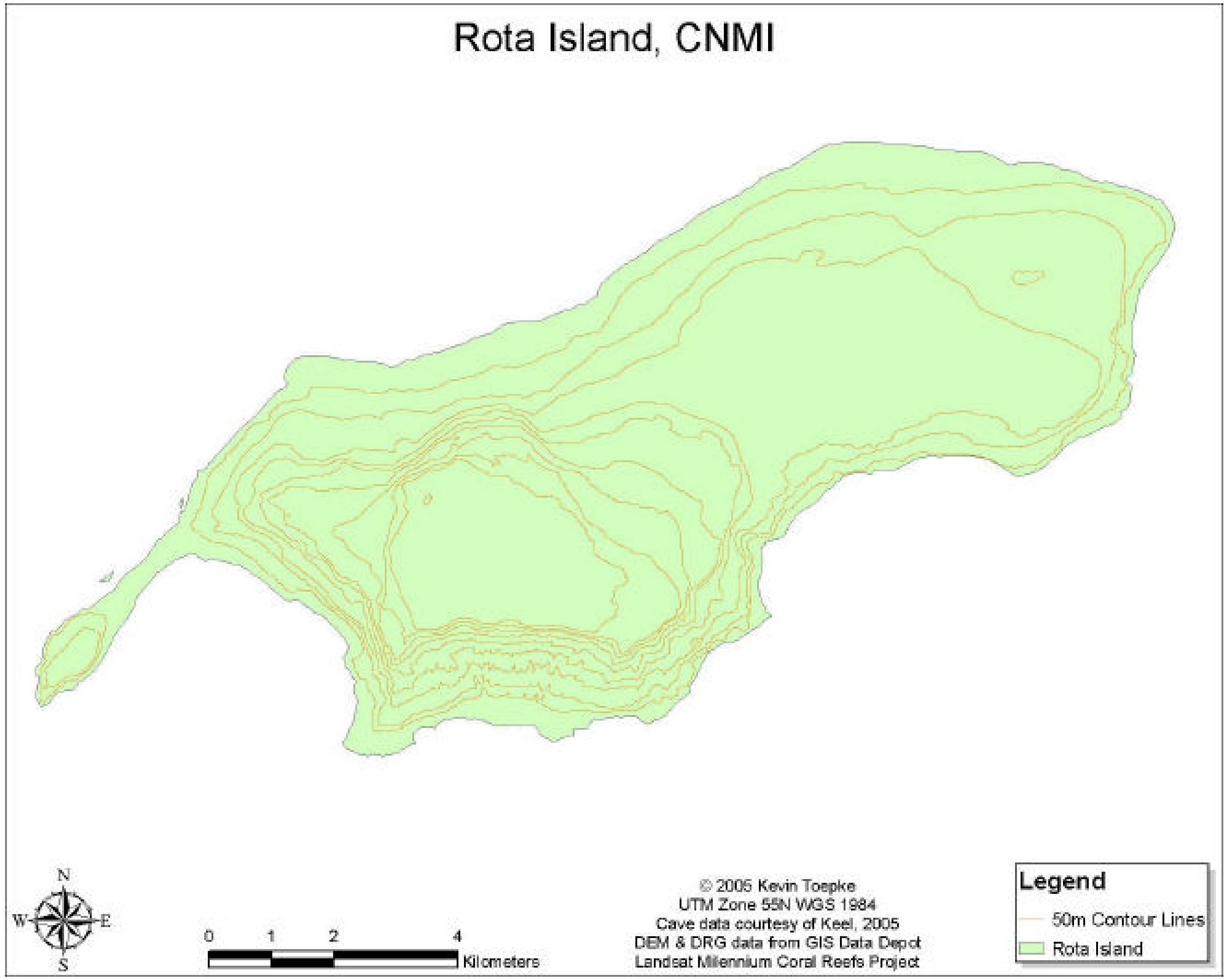


Figure 27: Map of Rota Island with island outline and 50m contour lines generated from the DEM of Rota Island

A Digital Raster Graphic (DRG) for Rota was acquired from USGS (2001v). The DRG was first converted to Erdas Imagine's Image format in Erdas Imagine then reprojected to WGS 1984 UTM Zone 55N using ArcToolbox, then finally loaded into the ArcMap document for Rota (Figure 28) and georectified to the LANDSAT image using the Reference tool within the Georeferencing toolbar in ArcMap.

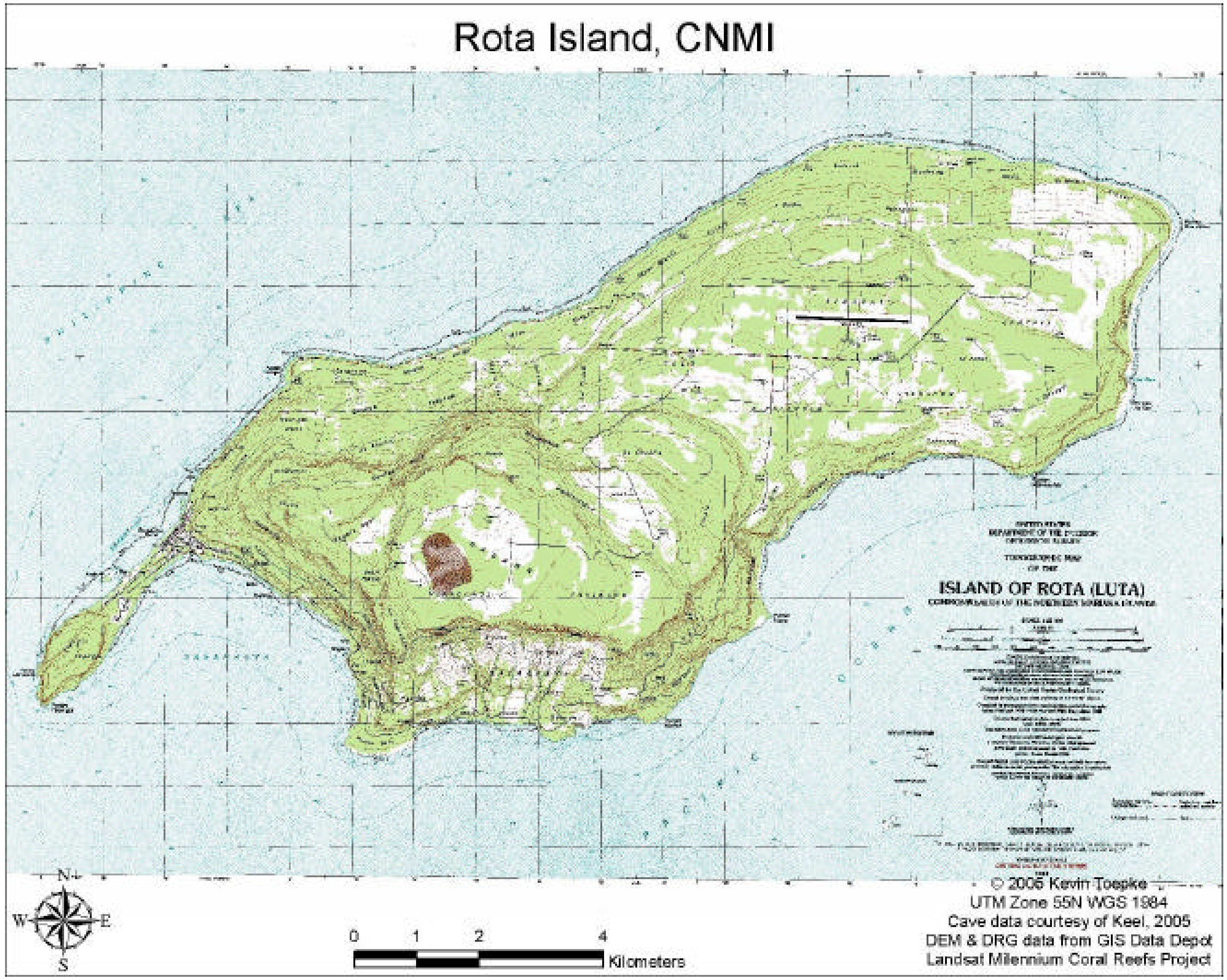


Figure 28: Map of Rota Island showing Digital Raster Graphics (DRG) Layer

Finally, two ArcScene documents were produced for visualization purposes. One with the true-color LANDSAT scene draped over the DEM (Figure 29) and one with the DRG draped over the DEM (Figure 30). In both cases, the appropriate image and the DEM were brought into ArcScene and the vertical exaggeration factors were set to the five times the elevation from the DEM.

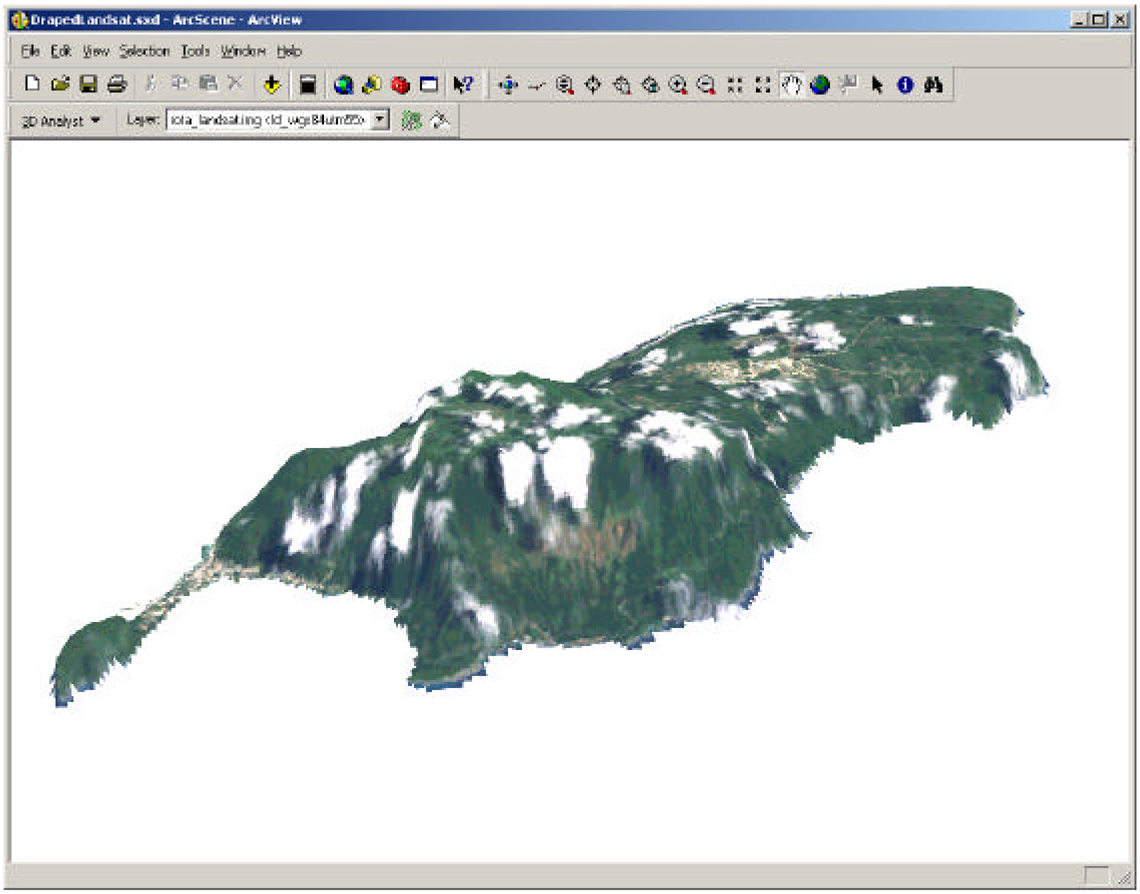


Figure 29: ArcScene of Rota's 1999 LANDSAT scene draped over the DEM with 5x vertical exaggeration

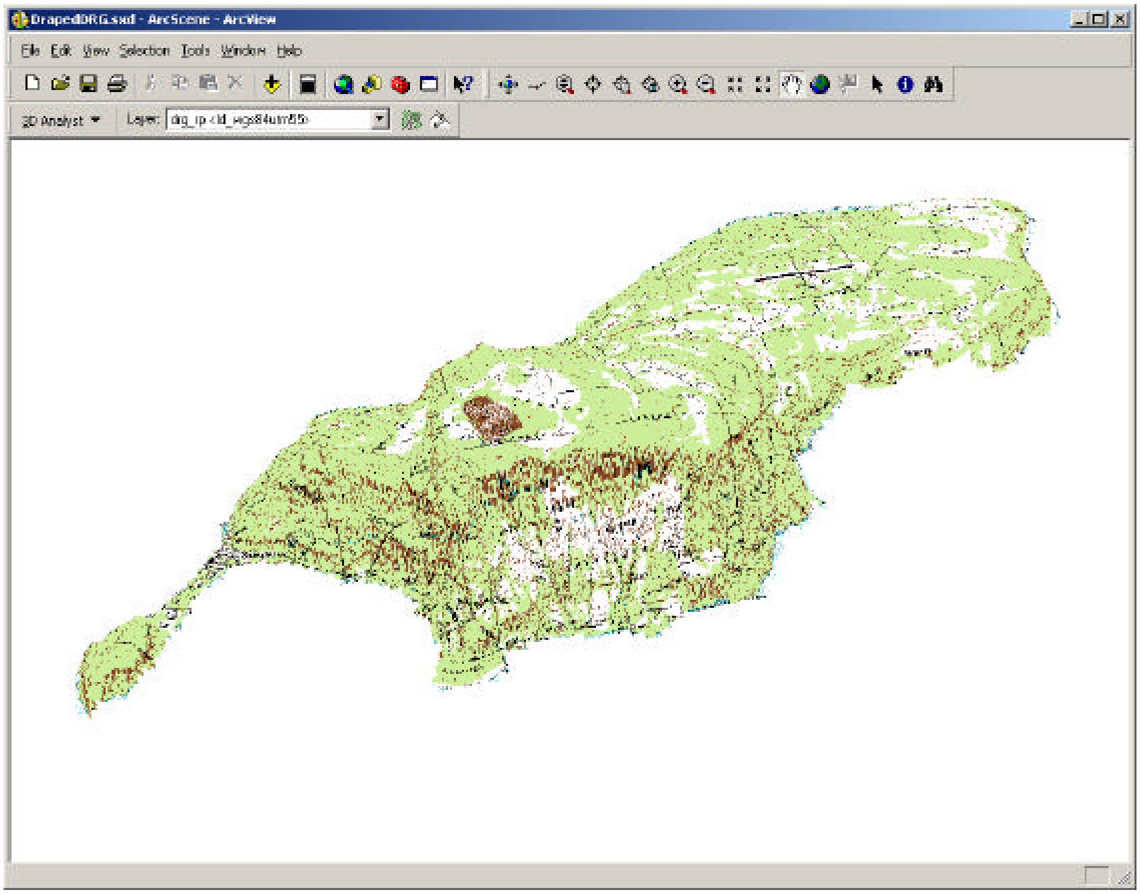


Figure 30: ArcScene of Rota's DRG draped over the DEM with 5x vertical exaggeration

Tinian

Stafford (2003) cataloged the cave and karst features of Tinian as part of the requirements for his Masters of Science degree from the Mississippi State University Department of Geosciences. It contains general locations and descriptions of the mapped karst features of Tinian broken down by cave type and physiographic province. The reduced survey data in Walls format, with location information; working cave maps in XaraX format; and final cave maps in JPEG format were received via personal communication with Stafford.

Once acquired, the data were initially split into directories, one for each cave. After the data were organized into separate directories for each cave, a vetting process took place to correctly identify each cave's type and physiographic province. The location data retrieved from the Walls files and the descriptions were used to vet the physiographic province information, and the cave maps and descriptions were used to vet the cave types. No inconsistencies in cave type or physiographic province were found across the data sources. The organized data for Tinian are summarized in Appendix E.

After the data were vetted, a directory was created for the island, subdirectories were created for each physiographic province, and further subdirectories were created for each cave type. Then the cave directories were moved to the correct cave type subdirectory.

When the data were organized a series of HTML pages was created, one for each feature. The HTML page was created in the directory for the feature. The HTML pages contain the cave descriptions and cave maps from Stafford (2003) as well as links to the Walls line plots and the XaraX working map files, if available.

The data were then loaded into a Microsoft Excel spreadsheet for easy manipulation. Once basic cleaning of the data had occurred, the data were then loaded into the Microsoft Access GDB using the import table command. The http_page_location field was then updated to the correct directory name using a SQL update statement. Once the data were in the GDB and fully populated, one layer file was created for each combination of cave type and physiographic province that exists in the GDB. The layer files were created in ArcCatalog and use a SQL query to pull information on the appropriate cave or karst features from the GDB. These layer files were then loaded into an ArcMap document for Tinian. Once in ArcMap, the display properties were modified to support hyperlinks based on the http_page_location field in the CAVES table, and the label properties were modified to label each feature using the name field in the CAVES table. Finally the symbology was changed to use a different symbol for each physiographic province and a different color for each cave type within physiographic province (Figure 31).

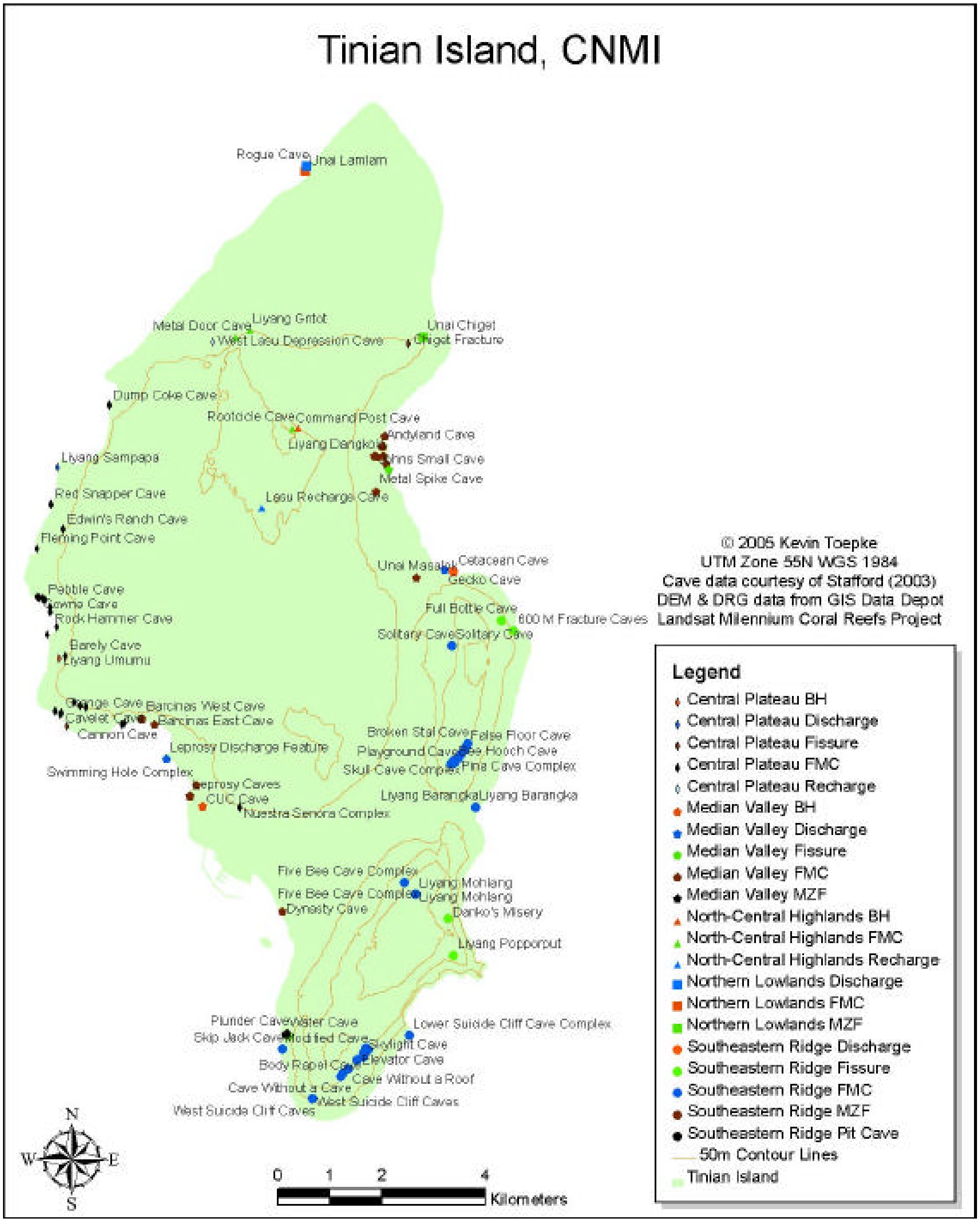


Figure 31: Map of Tinian with Cave Layers and Island Outline

The LANDSAT-7 scene that covers Tinian is Path 100, Row 50. The Millennium Coral Reef Project had scenes from two dates, 08/17/1999 (NASA, 2005c) and 03/15/2001 (NASA, 2005d), only the 2001 scene had less than 5% cloud cover. Erdas Imagine (Leica, 2002) was used to stack the multiple source image files into a multi-layer image file. Once complete, the scene was subsetted using a rectangular area of interest in Erdas Imagine to include just a small area around the island of Tinian. The subsetted 2001 scene was twice loaded into the ArcMap document (Figure 32 & Figure 33). The symbology on one of the scenes was changed to true-color (Band-1 to blue, Band-2 to green, Band-3 to red), and the other had its symbology changed to false-color IR (Band-2 to blue, Band-3 to green, Band-4 to red).

Figure 32: True Color LANDSAT-7 Image of Tinian Island

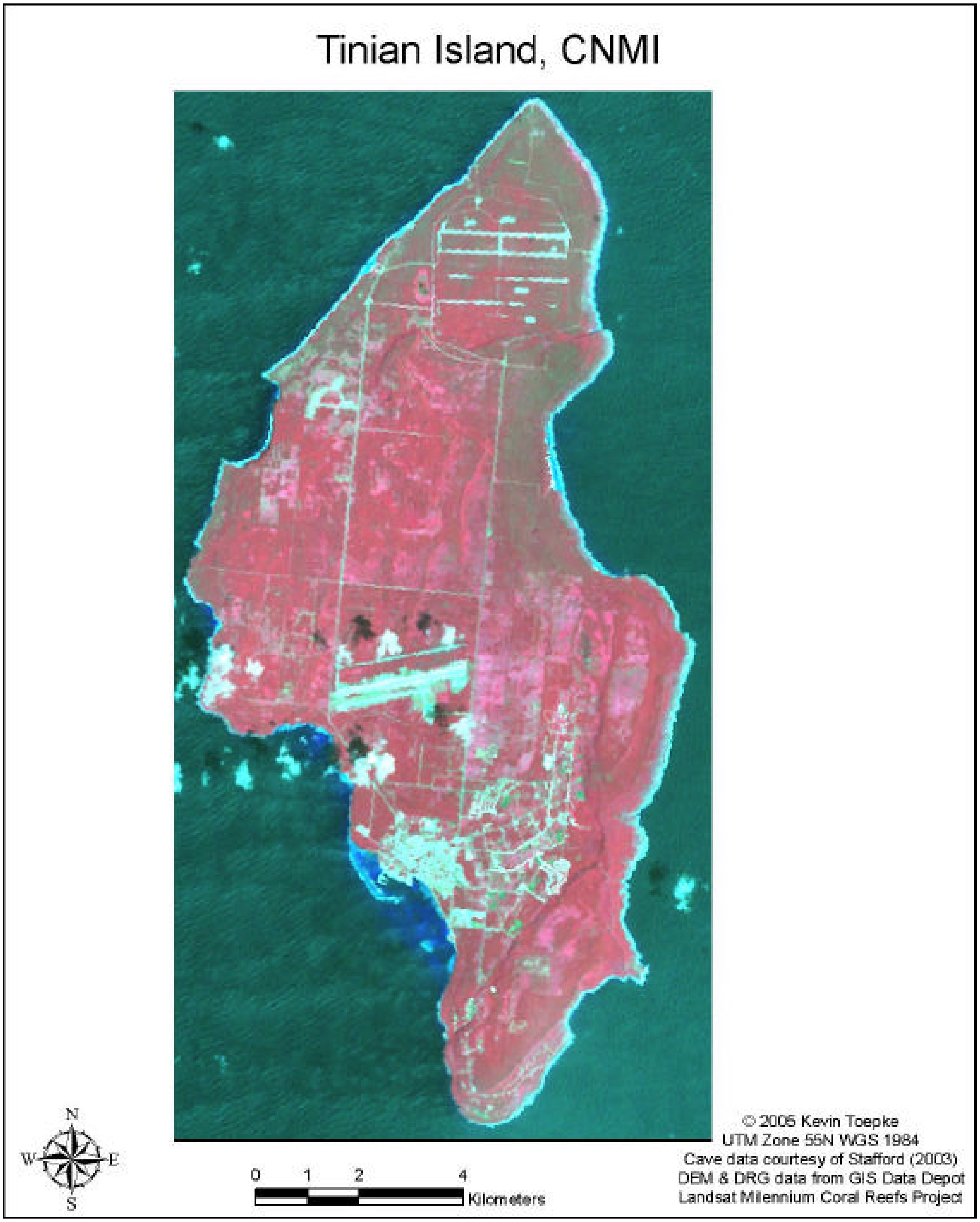


Figure 33: False Color IR LANDSAT-7 Image of Tinian Island

Digital Elevation Models for Tinian in the SDTS format were acquired from USGS (2001r, 2001s, 2001t, and 2001u). These DEMs were converted into GRID format using the sdts2grid program, and merged using ArcGIS grid command. After reprojecting the merged DEM to WGS 1984 UTM Zone 55N, the merged DEM was then loaded into the ArcMap document for Tinian (Figure 34). Upon loading the merged DEM into ArcMap, it was found that the DEM also needed to be georectified to the LANDSAT image. This was done using the Reference option in the Georeference toolbar in ArcMap. The LANDSAT image was chosen as truth because it more accurately lined up with the cave locations than the DEM.

Once the DEM was georectified the following computations were made on the DEM in Spatial Analyst: hillshade document (Figure 35) 10-m contour lines (Figure 36), 25-m contour lines (Figure 37), and 50-m contour lines (Figure 38). The contour lines were computed by using the contour option within Spatial Analyst, hillshade using the Hillshade option, and island outline was computed by using Raster Calculator to set all elevations less than or equal to zero to zero and all elevations greater than zero to one then converting the resulting grid data to a polygon using the Export Raster to Feature option in Spatial Analyst. Once the contour and island outline calculations were complete, the results were imported into the geodatabase using ArcCatalog's Import Feature Class (single) command. The resulting feature classes were then added to the ArcMap for Tinian and the symbology was changed to contour for the contour lines and a fill-color of green for the Island Outline.

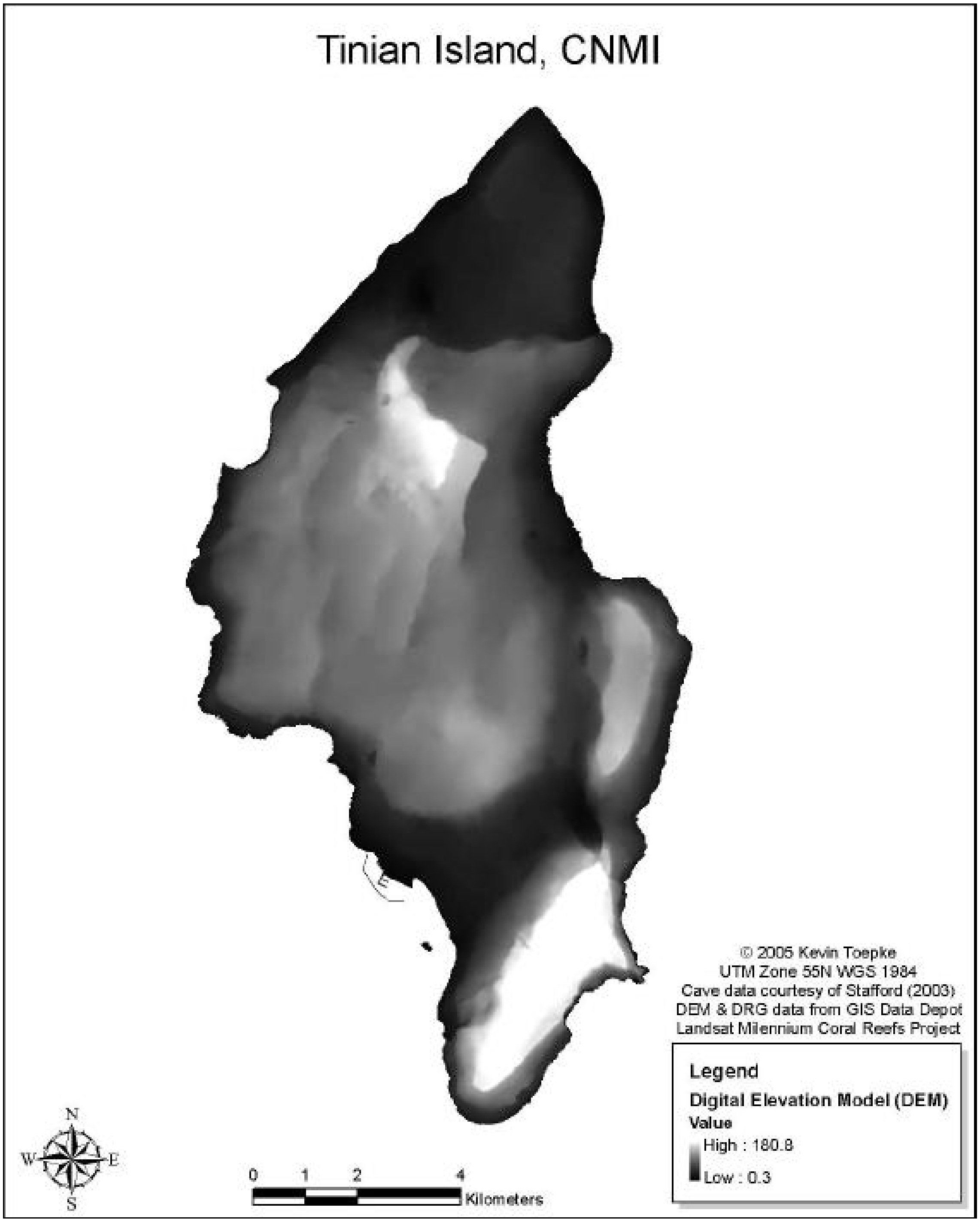


Figure 34: Digital Elevation Model (DEM) of Tinian Island

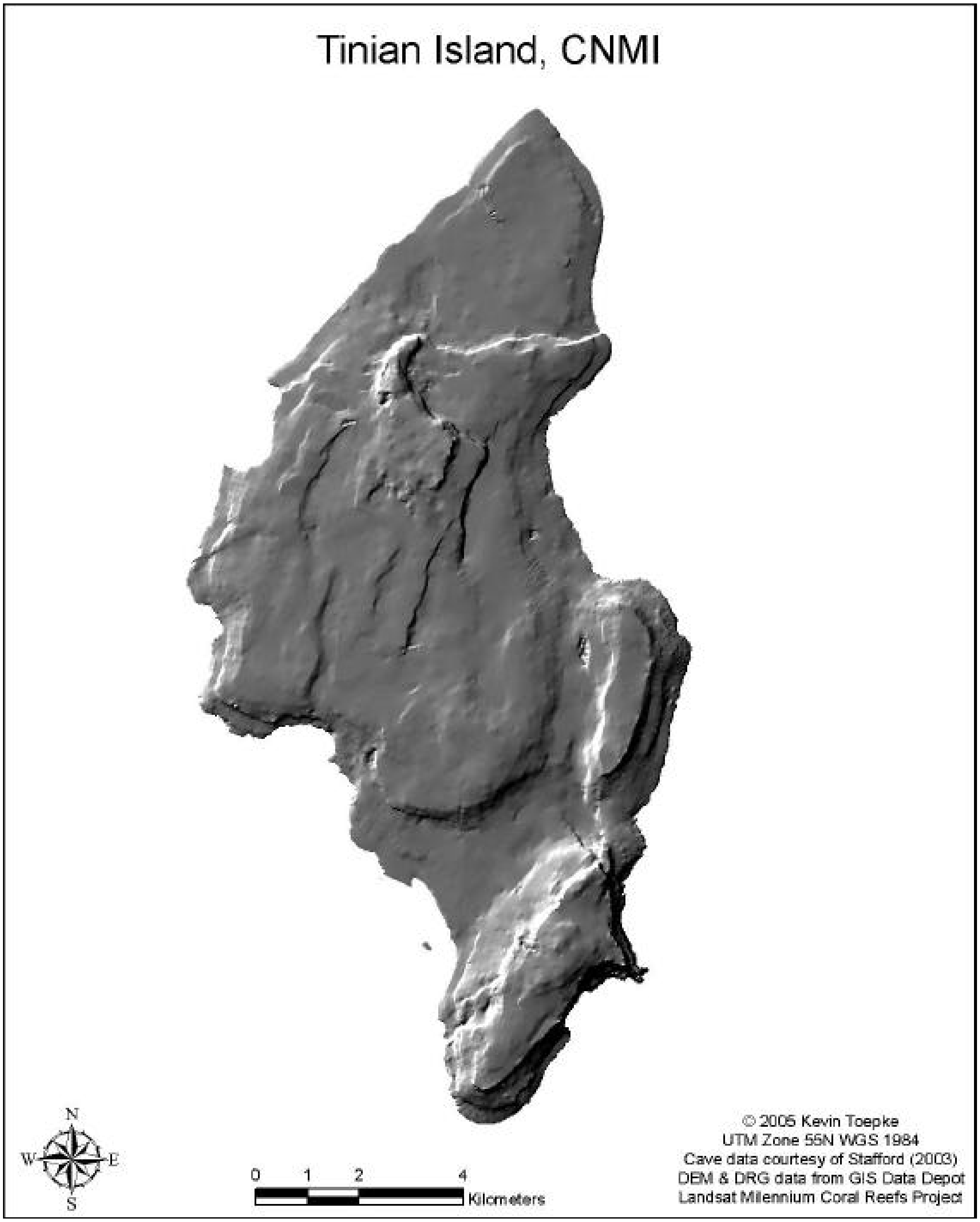


Figure 35: Hillshade of Tinian generated from the DEM of Tinian Island

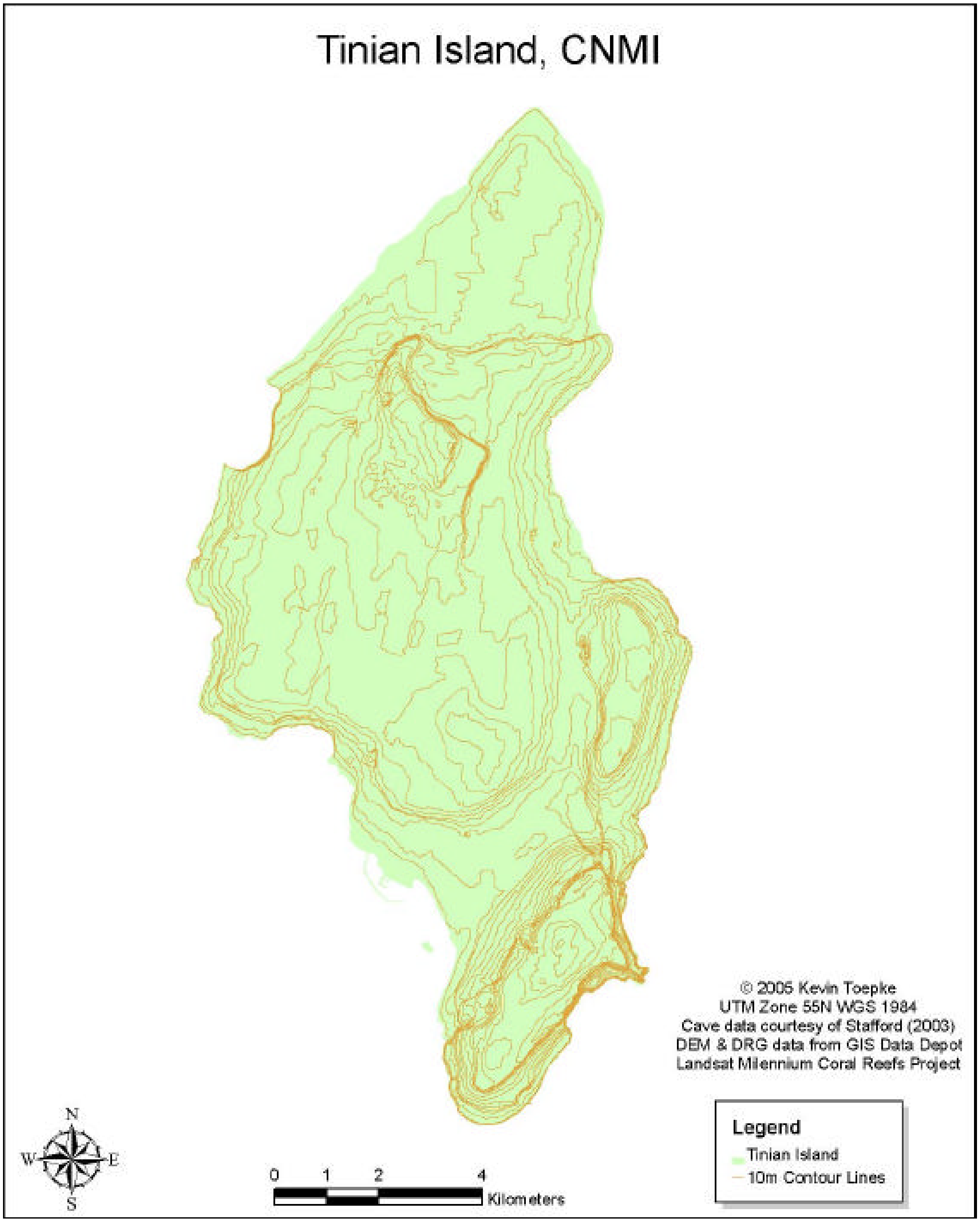


Figure 36: Map of Tinian Island with island outline and 10m contour lines generated from the DEM of Tinian Island

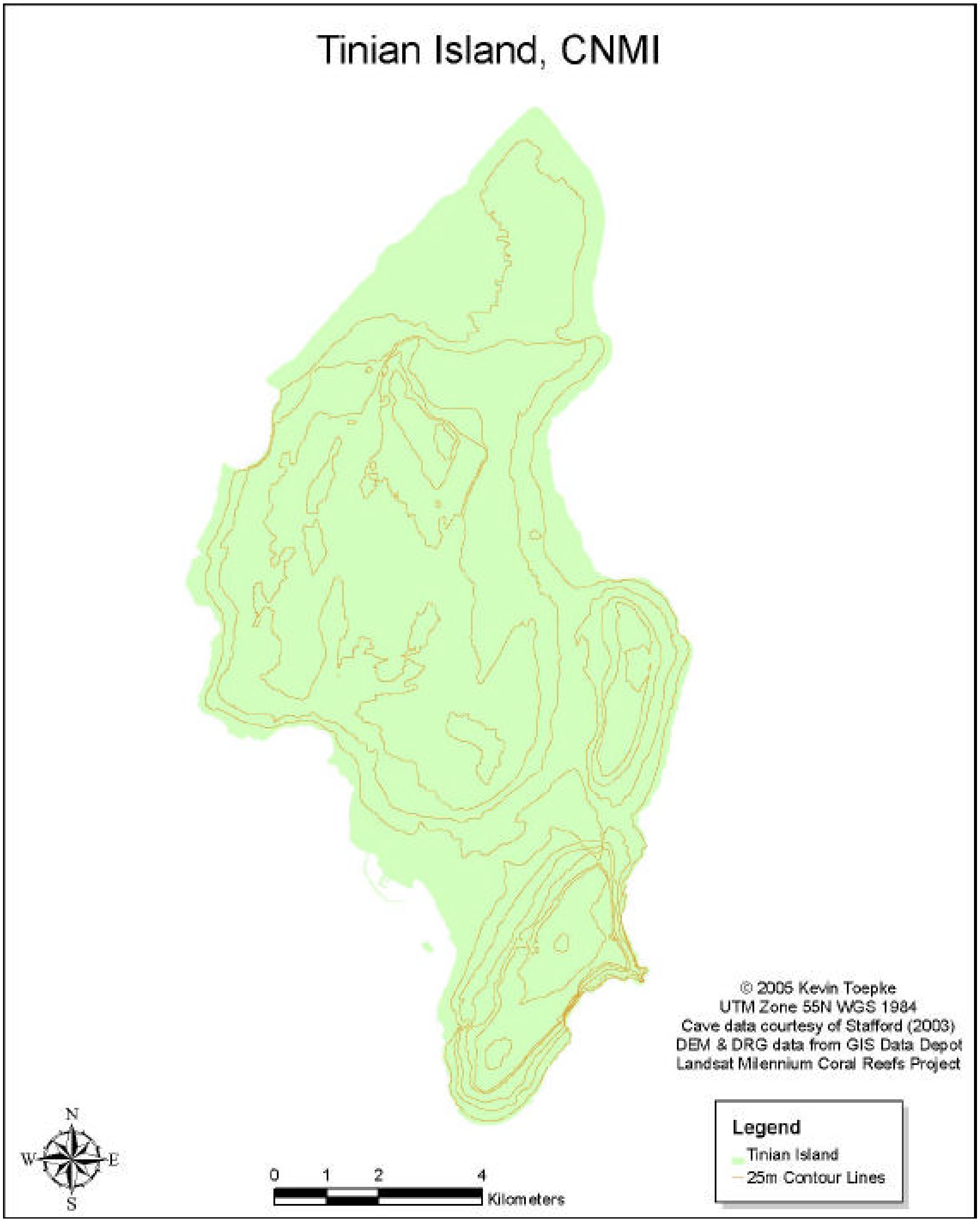


Figure 37: Map of Tinian Island with island outline and 25m contour lines generated from the DEM of Tinian Island

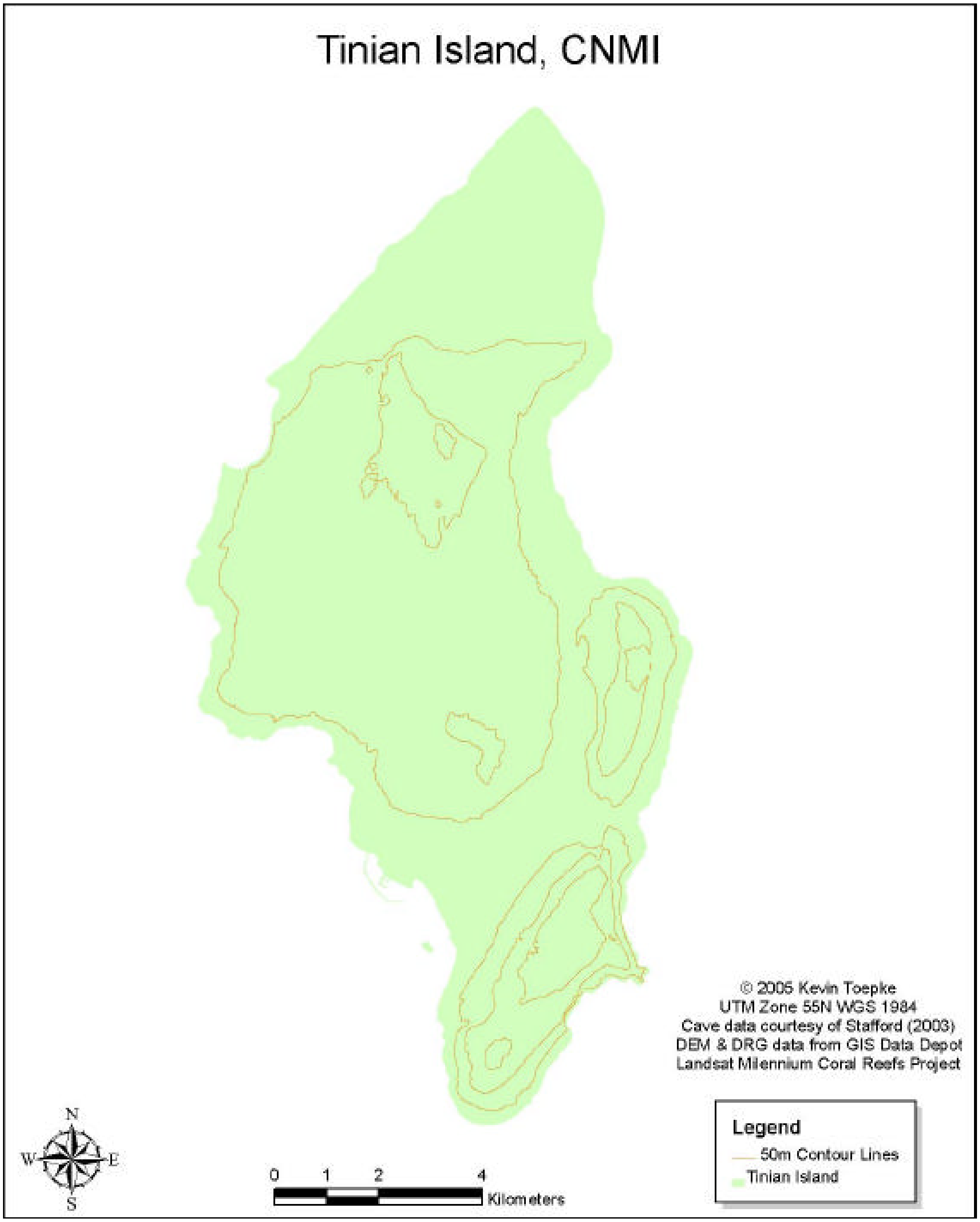


Figure 38: Map of Tinian Island with island outline and 50m contour lines generated from the DEM of Tinian Island

A Digital Raster Graphic (DRG) for Tinian and Aguijan was acquired from USGS (2001r). The DRG was first converted to Erdas Imagine's Image format in Erdas Imagine then reprojected to WGS 1984 UTM Zone 55N using ArcToolbox, then finally loaded into the ArcMap document for Tinian (Figure 39) and georectified to the LANDSAT image using the Reference tool within the Georeferencing toolbar in ArcMap.

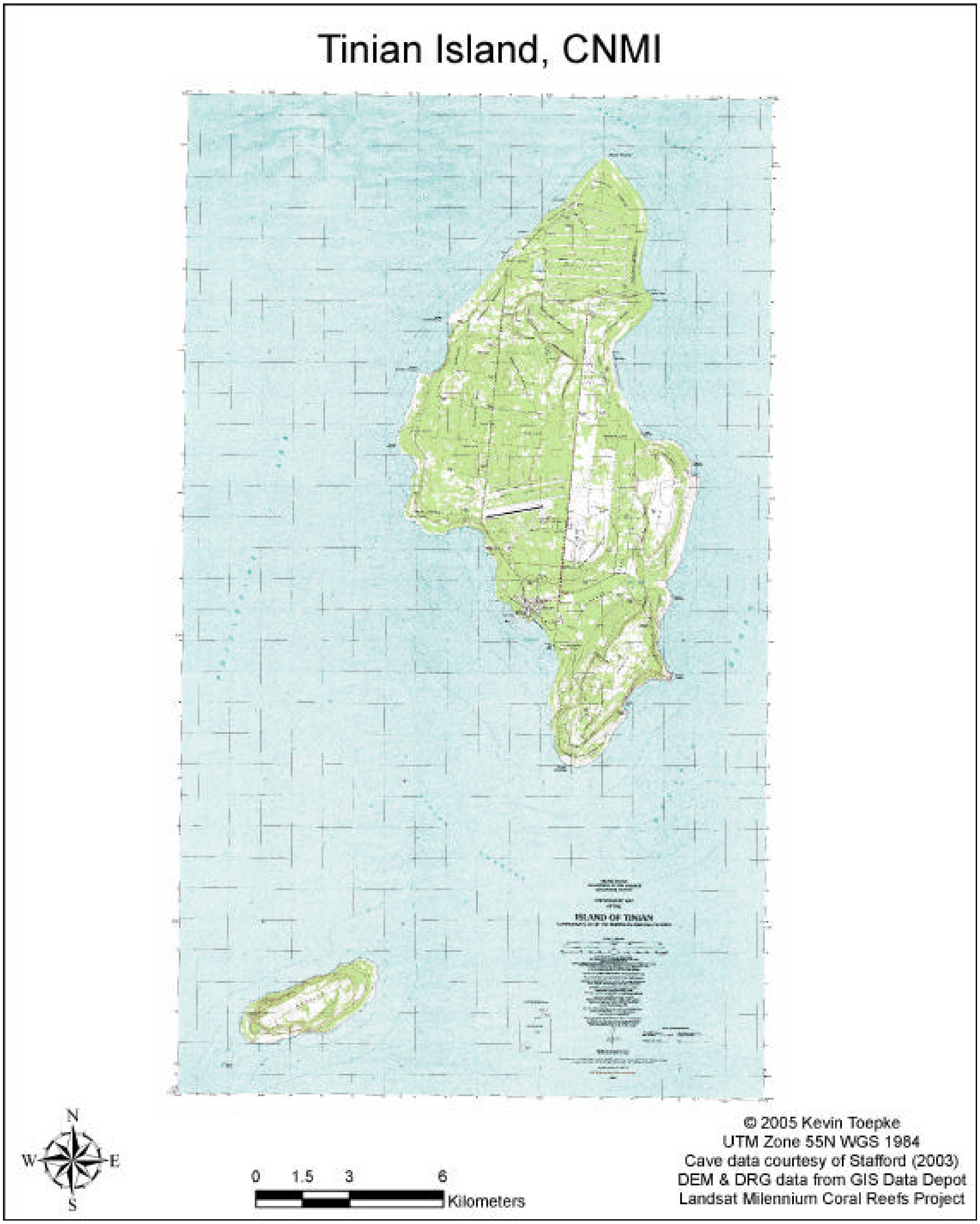


Figure 39: Map of Tinian and Aguijan Islands showing Digital Raster Graphics (DRG) Layer

Finally, two ArcScene documents were produced for visualization purposes. One with the true-color LANDSAT scene draped over the DEM (Figure 40) and one with the DRG draped over the DEM (Figure 41). In both cases, the appropriate image and the DEM were brought into ArcScene and the vertical exaggeration factors were set to the five times the elevation from the DEM.

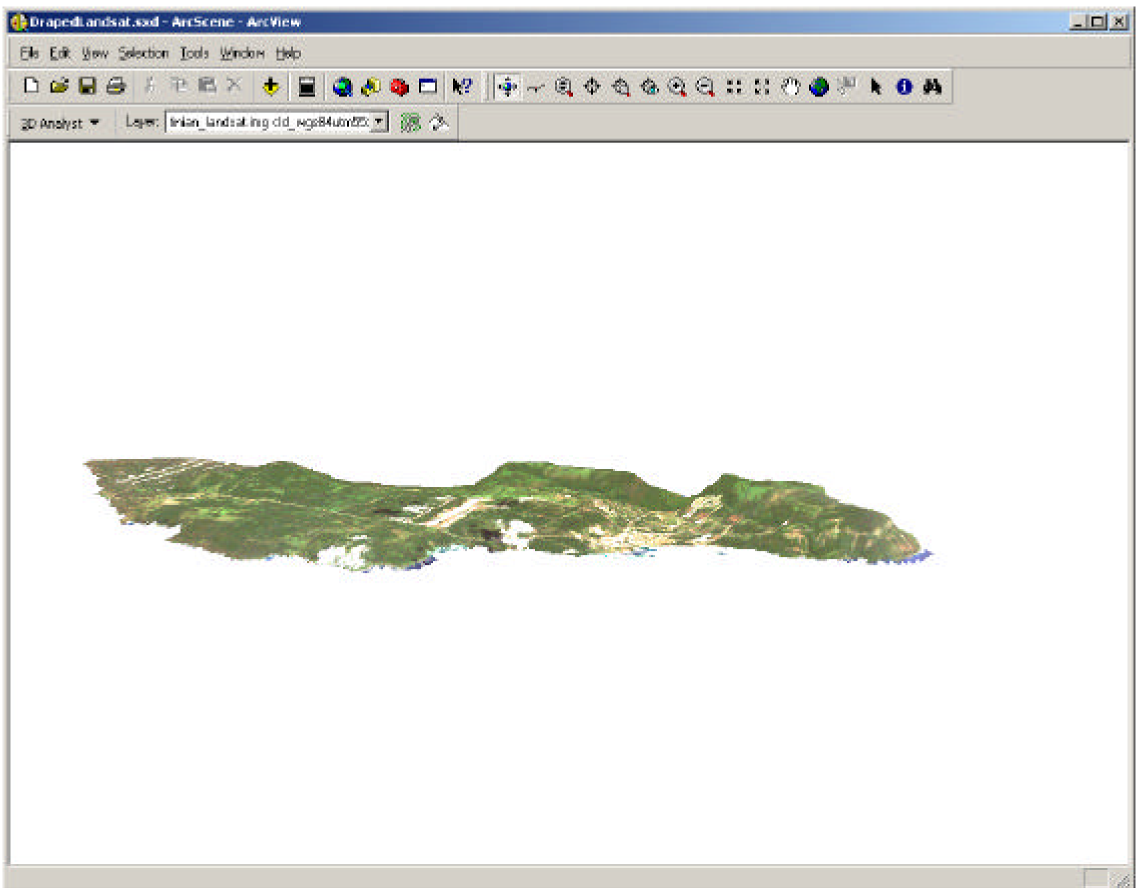


Figure 40: ArcScene of Tinian's LANDSAT scene draped over the DEM with 5x vertical exaggeration

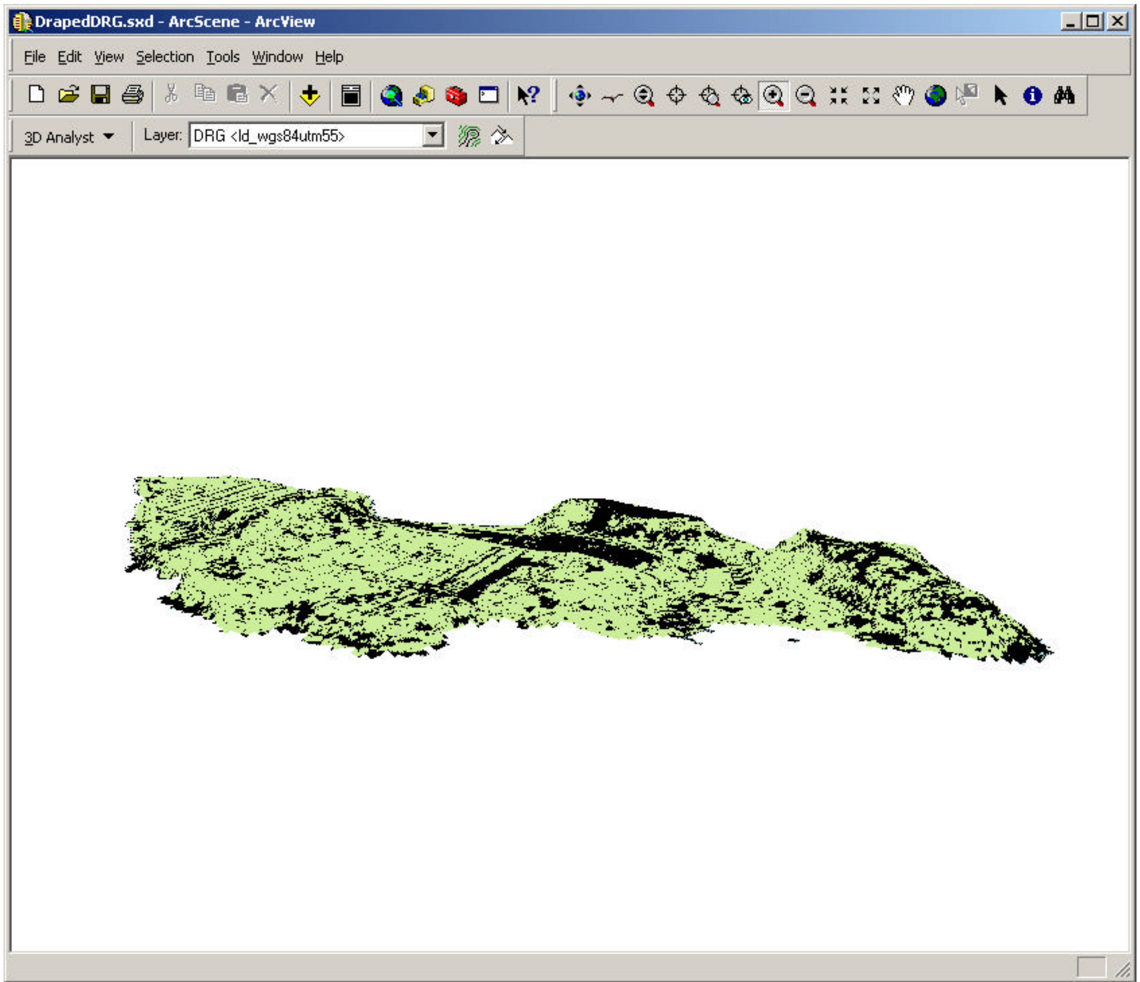


Figure 41: ArcScene of Tinian's DRG draped over the DEM with 5x vertical exaggeration

Guam

Taborosi (2000) cataloged the cave and karst features of Guam as part of the requirements for his Masters of Science degree from the University of Guam. It contains the locations of the mapped karst features of Guam. Taborosi's thesis was an inventory that only contained maps and descriptions of type examples. Because of this, Taborosi's thesis contained descriptions and descriptions for a small number of features.

Additional cave descriptions and maps were pulled from Taborosi (2004). The reduced survey data in Compass format as well as his preliminary GIS in ArcGIS format were received from Taborosi via personal communication. No source documents for the cave maps were received.

Once acquired, the data were initially split into directories, one for each karst feature. Within a cave or karst feature's directory, files were created for each of the following elements: cave description and cave map(s) in BMP format.

Some research had to be performed while organizing the data because cave naming was not consistent across the various sources. In addition, Taborosi divided karst features by Northern Guam karst features and Southern Guam karst features. Additional research had to be performed to identify the correct Southern Guam physiographic province each feature belonged in. A combination of the descriptions in Taborosi's thesis and the location data in the preliminary GIS were used to identify the correct physiographic province. A summary of these changes is in Table 6. The organized data for Guam are summarized in Appendix B.

Table 6: Southern Guam physiographic province changes for described or mapped karst features

Cave Name	Physiographic Province
Talofofo Cave #2	Southern Coast
Talofofo Caves	Southern Coast
Ito and *Minagawa* Sink	Southern Coast
Adjoulan Point Cave	Southern Coast
Asanite Cave	Southern Coast
Asquiroga Cave	Southern Coast
Mata Cave	Southern Coast
Matala Caves	Southern Coast
Orote Grottos	Southern Coast
Orote Window	Southern Coast
Tres Botsas	Southern Coast
Blue Hole	Southern Coast
Talofofo Pit Cave	Southern Coast
Lost River Rise Cliff Cave	Southern Interior Basin
Fena Sinkhole Cave	Southern Interior Basin
Bay Rum Cave	Southern Interior Basin
Liyang Almagosa Gelagu	Southern Mountain Range
Alamagosa Cave	Southern Mountain Range
Anae Caverns	Southern Mountain Range
Japanese Caves	Southern Mountain Range
Nimitz Hill Shelter Caves	Southern Mountain Range
Nimitz Hill Collapse Sink #1	Southern Mountain Range
Nimitz Hill Collapse Sink #2	Southern Mountain Range

When the data were organized a series of HTML pages was created, one for each feature. The HTML page was created in the directory for the feature. The HTML pages contain the cave descriptions and cave maps from Taborosi (2000, 2004) as well as links to the Compass project data, if available.

As previously mentioned, most of the karst features of Guam were not mapped or fully described in Taborosi's thesis. The vast majority of karst features were only listed with minimal information in appendices to his thesis and/or his preliminary GIS, which were received via personal communication with Taborosi in either Excel, or

ESRI shapefile format. In order to load the data contained from these sources into the GDB, the following process was followed. First, the projection information had to be defined for each layer using ArcToolbox. According to Taborosi, the information was in the Guam State Plane (feet) format. After the projection information was defined, the layers were reprojected to WGS 1984 UTM Zone 55N using ArcToolbox. In order to pull the location information from the reprojected layers two additional columns had to be added to the attribute table of each layer: UTM_North and UTM_East. These fields were then populated using a simple Visual Basic script available in the ArcMap help files. Once the fields were populated with the reprojected coordinates, the attribute table and the matching Excel spreadsheet were loaded into the GDB as linked tables via the import table command. The two linked tables were then joined via the common KARST_ID attribute and the contents were loaded into the CAVES table. Finally, the linked tables were removed from the GDB. The inventoried permitted store water disposal wells, the surface flow features, and the voids intercepted by drilling were not loaded into the GDB. Finally, the coastal discharge features were loaded into the GDB as discharge features.

Again, Taborosi only split the data into Northern and Southern Guam, so all of the features in Southern Guam had to have the correct physiographic province identified. Where the physiographic province had not been already identified, as above, the only location information was available to make the decision. A summary of the physiographic province changes made is in Table 7.

Table 7: Southern Guam physiographic province changes for karst features not described or mapped

Cave Name	Physiographic Province	Cave Name	Physiographic Province
Alifan ridge sink 1	Southern Mountain Range	Fena cockpit sink 19	Southern Interior Basin
Alifan ridge sink 2	Southern Mountain Range	Fena cockpit sink 2	Southern Interior Basin
Alifan ridge sink 3	Southern Mountain Range	Fena cockpit sink 20	Southern Interior Basin
Alifan ridge sink 4	Southern Mountain Range	Fena cockpit sink 21	Southern Interior Basin
Alifan ridge sink 5	Southern Mountain Range	Fena cockpit sink 22	Southern Interior Basin
Anae Island Cave	Southern Mountain Range	Fena cockpit sink 23	Southern Interior Basin
Asalonso Cave	Southern Coast	Fena cockpit sink 24	Southern Interior Basin
Asan depression 1	Southern Mountain Range	Fena cockpit sink 25	Southern Interior Basin
Asan depression 2	Southern Mountain Range	Fena cockpit sink 26	Southern Interior Basin
Asanite Road Caves	Southern Coast	Fena cockpit sink 27	Southern Interior Basin
Asanite sink	Southern Coast	Fena cockpit sink 28	Southern Interior Basin
Asiga Cave	Southern Coast	Fena cockpit sink 29	Southern Interior Basin
Assupian Cave	Southern Coast	*Fena* cockpit sink 30	Southern Interior Basin
Bonya River Arch	Southern Interior Basin	*Fena* cockpit sink 31	Southern Interior Basin
Bonya river sink 1	Southern Interior Basin	*Fena* cockpit sink 32	Southern Interior Basin
Bonya river sink 2	Southern Interior Basin	*Fena* cockpit sink 4	Southern Interior Basin
Bonya river sink 3	Southern Interior Basin	*Fena* cockpit sink 5	Southern Interior Basin
Bonya-Tolae Yu'us river	Southern Interior Basin	*Fena* cockpit sink 6	Southern Interior Basin
Cool Cave	Southern Coast	*Fena* cockpit sink 7	Southern Interior Basin
County Club depression	Southern Coast	*Fena* cockpit sink 8	Southern Interior Basin
Fena cockpit sink 1	Southern Interior Basin	*Fena* cockpit sink 9	Southern Interior Basin
Fena cockpit sink 10	Southern Interior Basin	*Fena* narrow sink	Southern Interior Basin
Fena cockpit sink 11	Southern Interior Basin	*Fena* cockpit sink 30	Southern Interior Basin
Fena cockpit sink 12	Southern Interior Basin	*Fena* cockpit sink 31	Southern Interior Basin
Fena cockpit sink 13	Southern Interior Basin	*Fena* cockpit sink 32	Southern Interior Basin
Fena cockpit sink 14	Southern Interior Basin	*Fena* cockpit sink 4	Southern Interior Basin
Fena cockpit sink 15	Southern Interior Basin	*Fena* cockpit sink 5	Southern Interior Basin
Fena cockpit sink 16	Southern Interior Basin	*Fena* cockpit sink 6	Southern Interior Basin
Fena cockpit sink 17	Southern Interior Basin	*Fena* cockpit sink 7	Southern Interior Basin
Fena cockpit sink 18	Southern Interior Basin	*Fena* cockpit sink 8	Southern Interior Basin

Table 7 (Continued)

Cave Name	Physiographic Province	Cave Name	Physiographic Province
Fonte Cave	Southern Mountain Range	Nimitz Hill depression 1	Southern Mountain Range
Gadao's Cave	Southern Coast	Nimitz Hill depression 2	Southern Mountain Range
Gumayas Chiget Cave	Southern Coast	Notre Dame School Caves	Southern Coast
Gumayas Guma'Yu'us Cave	Southern Coast	*Orote* Channel Cave	Southern Coast
Gumoje Cave	Southern Coast	*Orote* Cliff Cave	Southern Coast
Hoyo Matugan	Southern Mountain Range	*Orote* depression 1	Southern Coast
Hoyu Fena	Southern Interior Basin	*Orote* depression 2	Southern Coast
Hoyu Sabana Lamlam	Southern Mountain Range	*Orote* depression 3	Southern Coast
Ibaba Cave	Southern Interior Basin	*Orote* depression 4	Southern Coast
Liyang Namu Kanutu	Southern Interior Basin	*Orote Sagan Basula* Cave	Southern Coast
Lost River Cave	Southern Interior Basin	*Palasao* Cave	Southern Mountain Range
Maemong Bridge South	Southern Interior Basin	Pinnacle Cave	Southern Mountain Range
Maemong Rise	Southern Interior Basin	Pit Near Lost River Rise	Southern Interior Basin
Maemong River Cave	Southern Interior Basin	Suma Cave	Southern Coast
Malojloj depression 1	Southern Coast	*Taga'chang* Beach Pit	Southern Coast
Malojloj depression 2	Southern Coast	*Talofofo* Bay Overhang	Southern Coast
Malojloj depression 4	Southern Coast	*Talofofo* Cave #1	Southern Coast
Malojloj depression 5	Southern Coast	*Talofofo* Cave #3	Southern Coast
Malojloj depression 6	Southern Coast	*Talofofo* Cave #4	Southern Coast
Malojloj depression 7	Southern Coast	*Talofofo* Cave #5	Southern Coast
Malojloj landfill	Southern Coast	*Talofofo* Cave #6	Southern Coast
Manengon sink	Southern Coast	*Talofofo* depression 1	Southern Coast
Meamong Bridge North	Southern Interior Basin	*Talofofo* depression 2	Southern Coast

Table 7 (Continued)

Cave Name	Physiographic Province	Cave Name	Physiographic Province
Mt. Almagosa Caves	Southern Mountain Range	Talofofo depression 3	Southern Coast
Mt. Alutom Cave	Southern Mountain Range	Talofofo depression 4	Southern Coast
Nimitz Hill Cave	Southern Mountain Range	Talofofo depression 5	Southern Coast
Talofofo depression 6	Southern Coast	Tolae Yu'us Cave	Southern Interior Basin
Talofofo depression 7	Southern Coast	Tolae Yu'us Kinahulo'guan	Southern Interior Basin
Talofofo golf course sink 1	Southern Coast	Virgin Mary Shelter Cave	Southern Mountain Range
Talofofo golf course sink 2	Southern Coast	Window Rock	Southern Coast
Talofofo Pit Cave	Southern Coast	Ylig Bay Cave	Southern Coast
Tipalao Cave	Southern Coast	Yona depression 1	Southern Coast
Tipoco Island Arch	Southern Coast	Yona depression 2	Southern Coast
Togcha depression	Southern Coast		

Table 8: Feature type classification changes from Taborosi (2000)

Feature Name	Updated Classification	Original Classification
Awesome Cave	Contact Cave	Stream Cave
Barrigada Sink	Abandoned Stream Cave	Closed Depression
Bay Rum Cave	Mixing-zone Fracture Cave	Stream Cave
Blue Hole	Pit Cave	Submerged Pit Cave
Carino Sink Cave	Abandoned Stream Cave	Ex-Conduit
Castro's Beachrock Sink	Flank Margin Cave	Fracture
Chalam Pago Uvala	Closed Depression	Uvala
Coconut Crab Cave	Discharge Feature	Fracture
Dededo Gulf Course Ponding Basin 1	Closed Depression	Unknown
Dededo Gulf Course Ponding Basin 2	Closed Depression	Unknown
Devol's Punchbowl	Flank Margin Cave	Collapse Feature
Fena Sinkhole Cave	Stream Cave	Ephemeral Stream Cave
Gayinero Sink a	Closed Depression	Border Polje
Gayinero Sink b	Closed Depression	Allogenic P.R.
Guacluluyau sink (north)	Closed Depression	Valley Sink
Haputo Sink 1	Closed Depression	Drawdown
Haputo Sink 2	Closed Depression	Drawdown
Haputo Sink 3	Closed Depression	Drawdown
Haputo Sink 4	Closed Depression	Drawdown
Haputo Sink 5	Closed Depression	Drawdown
Haputo Sink 6	Closed Depression	Drawdown
Harmon sink (a)	Closed Depression	Autogenic P.R
Harmon sink (b)	Closed Depression	Unknown Origin
Harmon sink (c)	Closed Depression	Autogenic P.R
Hawaiian Sink 1	Closed Depression	Drawdown
Hawaiian Sink 2	Closed Depression	Unknown Origin
Interesting Sink	Closed Depression	Allogenic P.R.
Ito & Minagawa Sink	Banana Hole	Collapse Sink
Janum Spring Cave	Stream Cave	Spring
Lafac Grotto	Flank Margin Cave	Collapse Feature
Lafac-Anao Collapse 3	Unknown Origin	Collapse Feature
Mata Cave	Flank Margin Cave	Unknown Origin
Mataguac Spring Cave	Discharge Feature	Stream Cave
Mataguac Spring Sink	Closed Depression	Stream Cave

Table 8 (Continued)

Feature Name	Updated Classification	Original Classification
Matt's Cave	Flank Margin Cave	Submerged Feature
Menpachi	Mixing-zone Fracture Cave	Fracture
Mt. Santa Rosa Cave	Closed Depression	Stream Cave
Nimitz Hill Depression 1	Closed Depression	Unknown
Nimitz Hill Depression 2	Closed Depression	Unknown
No Can	Mixing-zone Fracture Cave	Fracture
Orote Grotto (north)	Flank Margin Cave	Collapse
Orote Grotto (south)	Flank Margin Cave	Collapse
Orote Window	Flank Margin Cave	Collapse
Pagat Sea Arch	Unknown Origin	Collapse Feature
Piggy Cave	Contact Cave	Stream Cave
Pinate Sink 1	Closed Depression	Drawdown
Pinate Sink 2	Closed Depression	Drawdown
Pinate Sink 3	Closed Depression	Drawdown
Pinate Sink 4	Closed Depression	Drawdown
Ritidian Double Arch	Flank Margin Cave	Collapse Feature
Scott's Fracture	Mixing-zone Fracture Cave	Fracture
Talofofo Cave #1	Abandoned Stream Cave	Paleo-Stream
Talofofo Cave #2	Abandoned Stream Cave	Paleo-Stream
Talofofo Cave #3	Abandoned Stream Cave	Paleo-Stream
Talofofo Cave #4	Abandoned Stream Cave	Paleo-Stream
Talofofo Cave #5	Abandoned Stream Cave	Paleo-Stream
Talofofo Cave #6	Abandoned Stream Cave	Paleo-Stream
Tarague Beach View Cave	Flank Margin Cave	Unknown
Tarague Copra Cave	Closed Depression	Unknown
Tarague Well #1	Closed Depression	Closed Depression - Cenote
Tarague Well #2	Closed Depression	Closed Depression - Cenote
Tarague Well #3	Closed Depression	Closed Depression - Cenote
Tarague Well #4	Closed Depression	Closed Depression - Cenote
Tarague Well #6	Closed Depression	Closed Depression - Cenote
Tarague Well #7	Closed Depression	Closed Depression - Cenote
Tarague Well #8	Closed Depression	Closed Depression - Cenote

The http_page_location field was then manually updated to the correct directory name for the feature. Where a description or map was for multiple features, the same directory name was placed in the http_page_location for each feature.

Once the data were in the GDB and fully populated, one layer file was created for each combination of cave type and physiographic province that exists in the GDB. The layer files were created in ArcCatalog and use a SQL query to pull information on the appropriate cave or karst features from the GDB. The layer files were created in ArcCatalog and use a SQL query to pull information on the appropriate cave or karst features from the GDB. These layer files were then loaded into an ArcMap document for Guam. Once in ArcMap, the display properties were modified to support hyperlinks based on the http_page_location field in the CAVES table, and the label properties were modified to label each feature using the name field in the CAVES table. Finally the symbology was changed to use a different symbol for each physiographic province and a different color for each cave type within physiographic province (Figure 42).

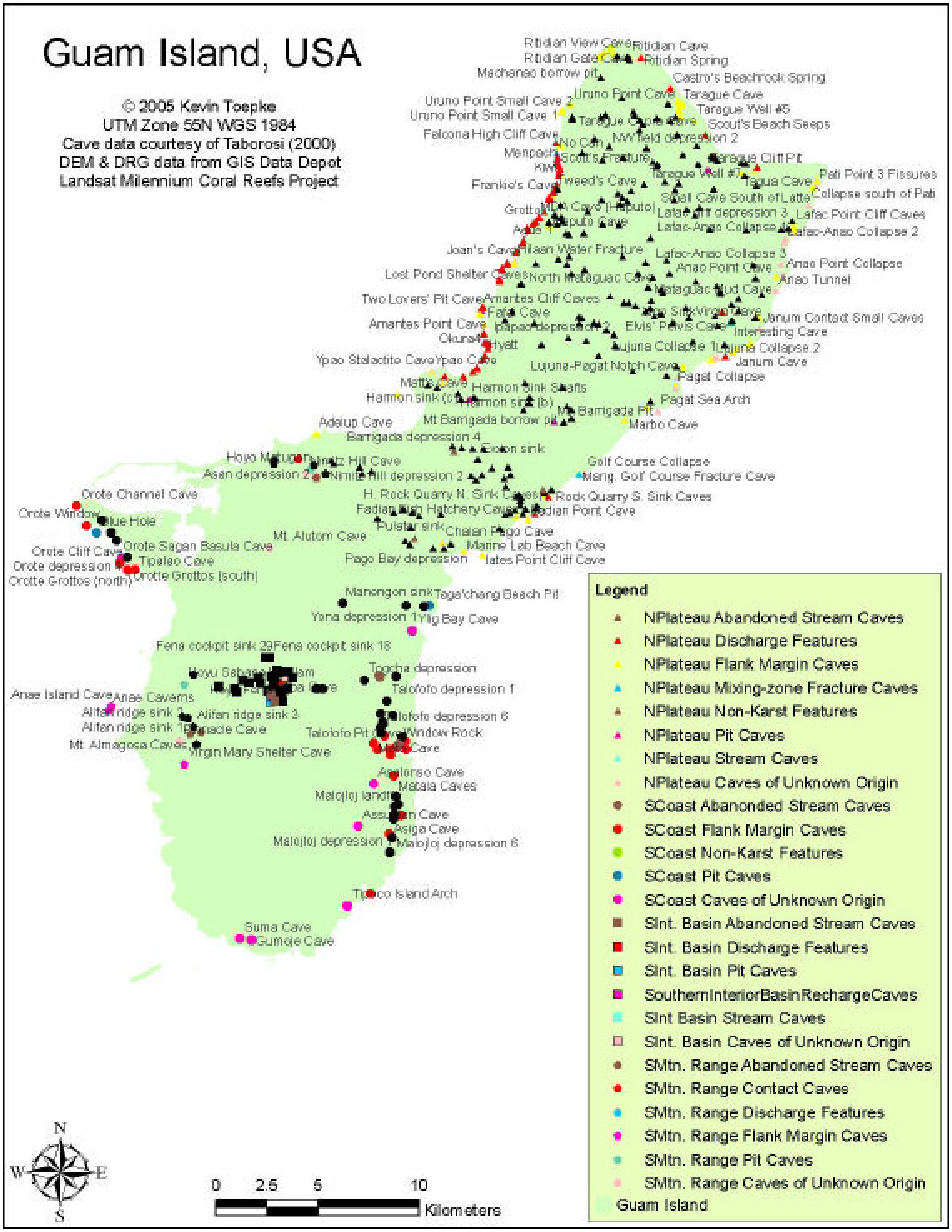


Figure 42: Map of Guam with Cave Layers and Island Outline

The descriptive GIS produced by Taborosi had many additional layers of interest to karst researchers including loosing streams, sinking streams, artificial ponding basins, and others. ArcMap was able to define projections for the 18 of the layers they were imported into the GDB after reprojecting them to WGS 1984 UTM Zone 55N then they added to Guam's map (Table 9, Figure 43).

Table 9: Layers from Taborosi's GIS that were added to the GDB

Layer Filename	Layer Type	Contents	GDB Feature Name
artificial	Line	Artificial Closed Depressions	GuamArtificialClosedDepressions
contact	Line	Exposed Volcanic Contact	GuamVolcanicContact
Faults-feet	Line	Faults in Northern Guam	NorthGuamFaults
Faults-feet (South)	Line	Faults in Southern Guam	SouthGuamFaults
loosing	Line	Loosing Streams	GuamLoosingStreams
main roads	Line	Main roads on Guam	MainRoadsGuam
pagoadelup	Line	Pago-Adelup Fault	PagoAdelupFault
ponding	Line	Artificial Ponding Basins	GuamPondingBasins
Ponding basins	Point	Locations of Ponding Basins in Northern Guam	NorthGuamPondingBasins
quarries	Line	Quarries	GuamQuarries
RIV1	Polygon	Inland water bodies (lakes and reservoirs)	GuamLakes
RIV2	Line	Rivers in Southern Guam	SouthGuamRivers
river-rise	Point	Resurgences	GuamResurgences
ROADS	Line	All roads on Guam	AllGuamRoads
sinking	Line	Sinking Streams	GuamSinkingStreams
Sub-basins-feet	Line	Watershed delimitations	NorthGuam
SWAMPF	Polygon	Swamps	GuamSwamps
volcanics	Line	Theoretical subsurface volcanic contact for northern guam	NorthGuamVolcanicSurface

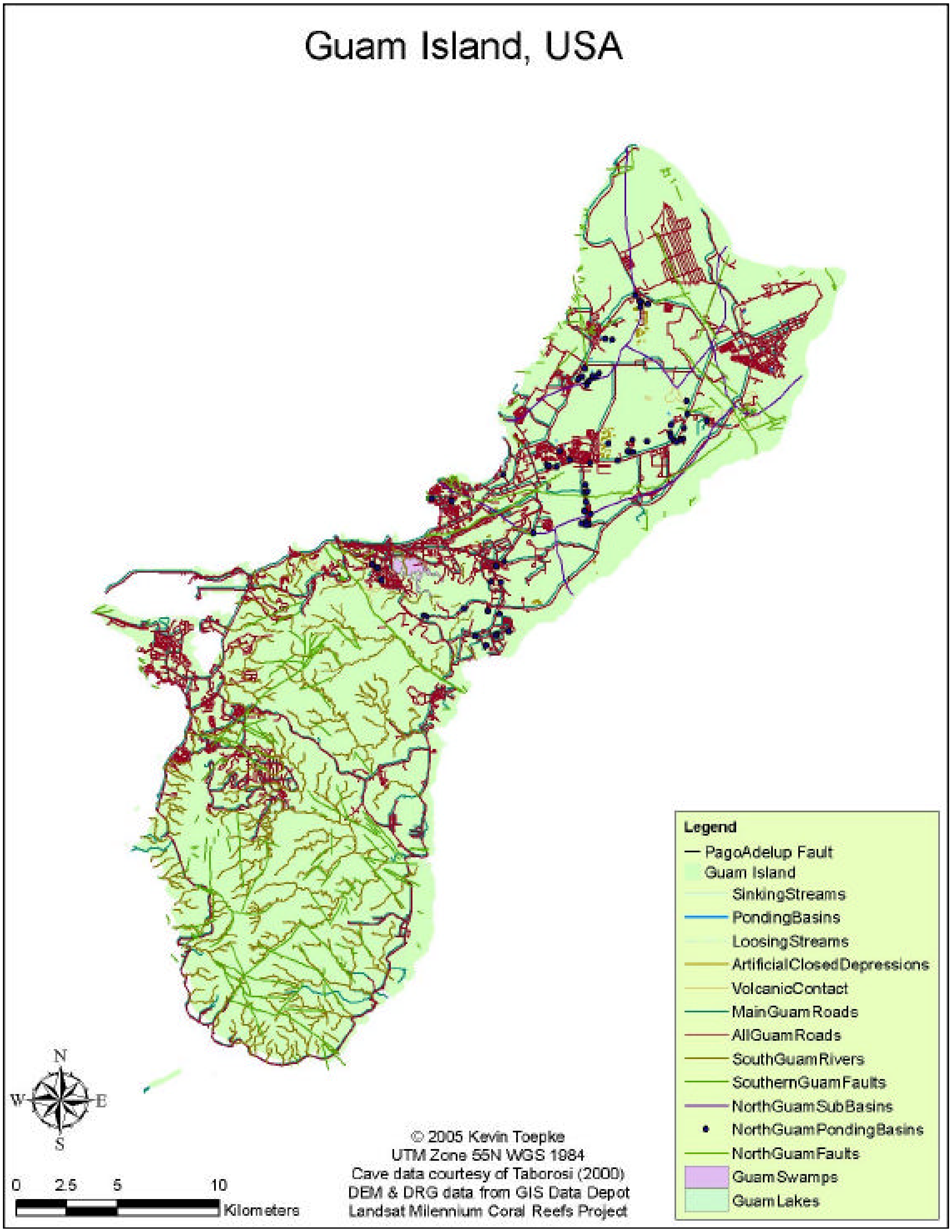


Figure 43: Map of Guam showing layers imported from Taborosi's GIS

The LANDSAT-7 scene that covers Guam is Path 100, Row 51. The Millennium Coral Reef Project had scenes from three dates, 08/17/1999, 01/10/2002, and 03/15/2001 (NASA, 2005d,e). Only the March 2001 scene had less than 5% cloud cover. Erdas Imagine was used to stack the multiple source image files into a multi-layer image file. Once complete, the scene was subsetted using a rectangular area of interest in Erdas Imagine to include just a small area around the island of Guam. The subsetted 2001 scene was twice loaded into the ArcMap document (Figure 44 & Figure 45). The symbology on one of the scenes was changed to true-color (Band-1 to blue, Band-2 to green, Band-3 to red), and the other had its symbology changed to false-color IR (Band-2 to blue, Band-3 to green, Band-4 to red).

Figure 44: True Color LANDSAT-7 Image of Guam Island

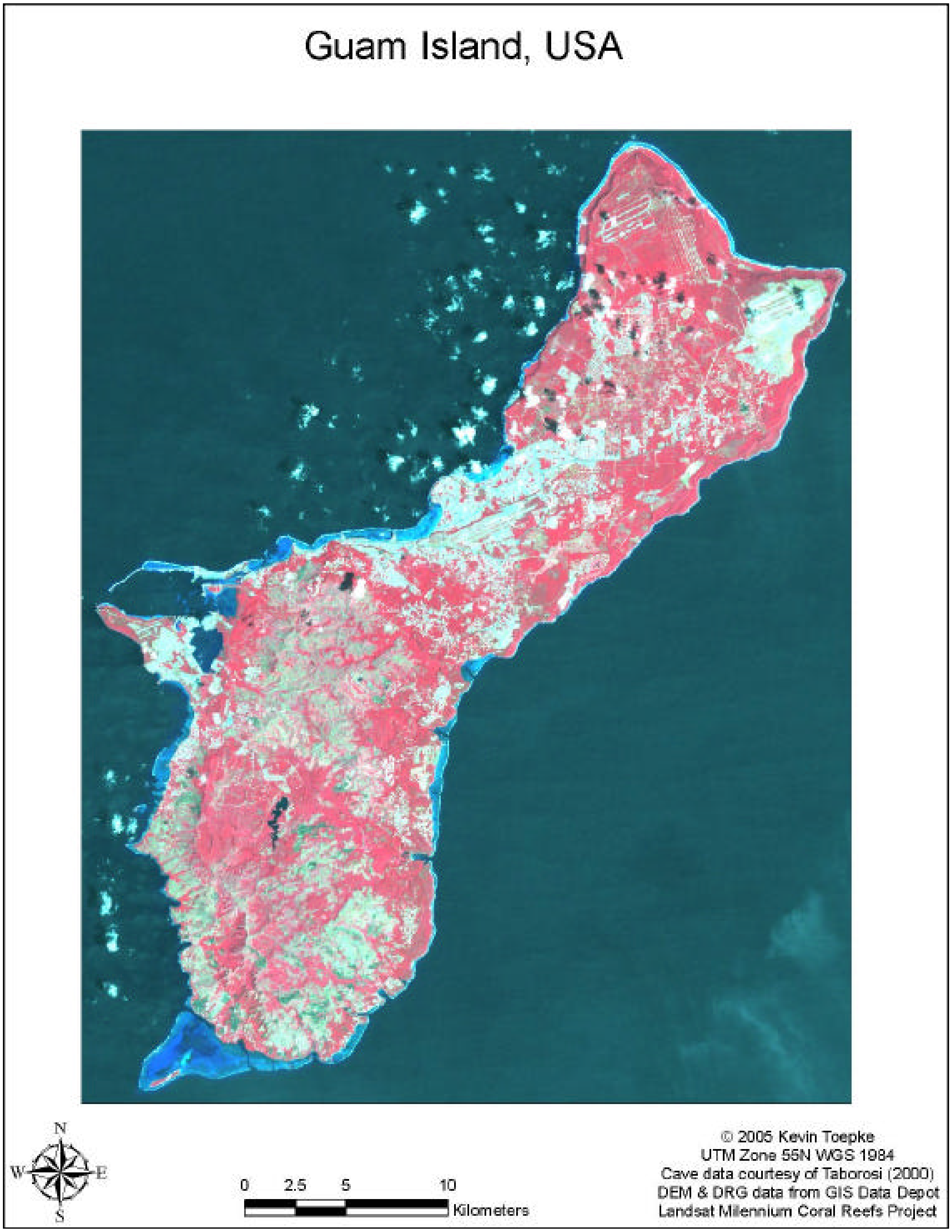


Figure 45: False Color IR LANDSAT-7 Image of Guam Island

Digital Elevation Models for Guam in the SDTS format were acquired from USGS (2001k-q). These DEMs were converted into GRID format using the sdts2grid program, and merged using ArcGIS grid command. After reprojecting the merged DEM to WGS 1984 UTM Zone 55N, the merged DEM was then loaded into the ArcMap document for Guam (Figure 46) and the following computations were made on the DEM in Spatial Analyst: hillshade document (Figure 47), 10-m contour lines (Figure 48), 25-m contour lines (Figure 49), and 50-m contour lines (Figure 50). The contour lines were computed by using the contour option within Spatial Analyst, hillshade using the Hillshade option, and island outline was computed by using Raster Calculator to set all elevations less than or equal to zero to zero and all elevations greater than zero to one then converting the resulting grid data to a polygon using the Export Raster to Feature option in Spatial Analyst. Once the contour and island outline calculations were complete, the results were imported into the geodatabase using ArcCatalog's Import Feature Class (single) command. The resulting feature classes were then added to the ArcMap for Guam and the symbology was changed to contour for the contour lines and a fill-color of green for the Island Outline.

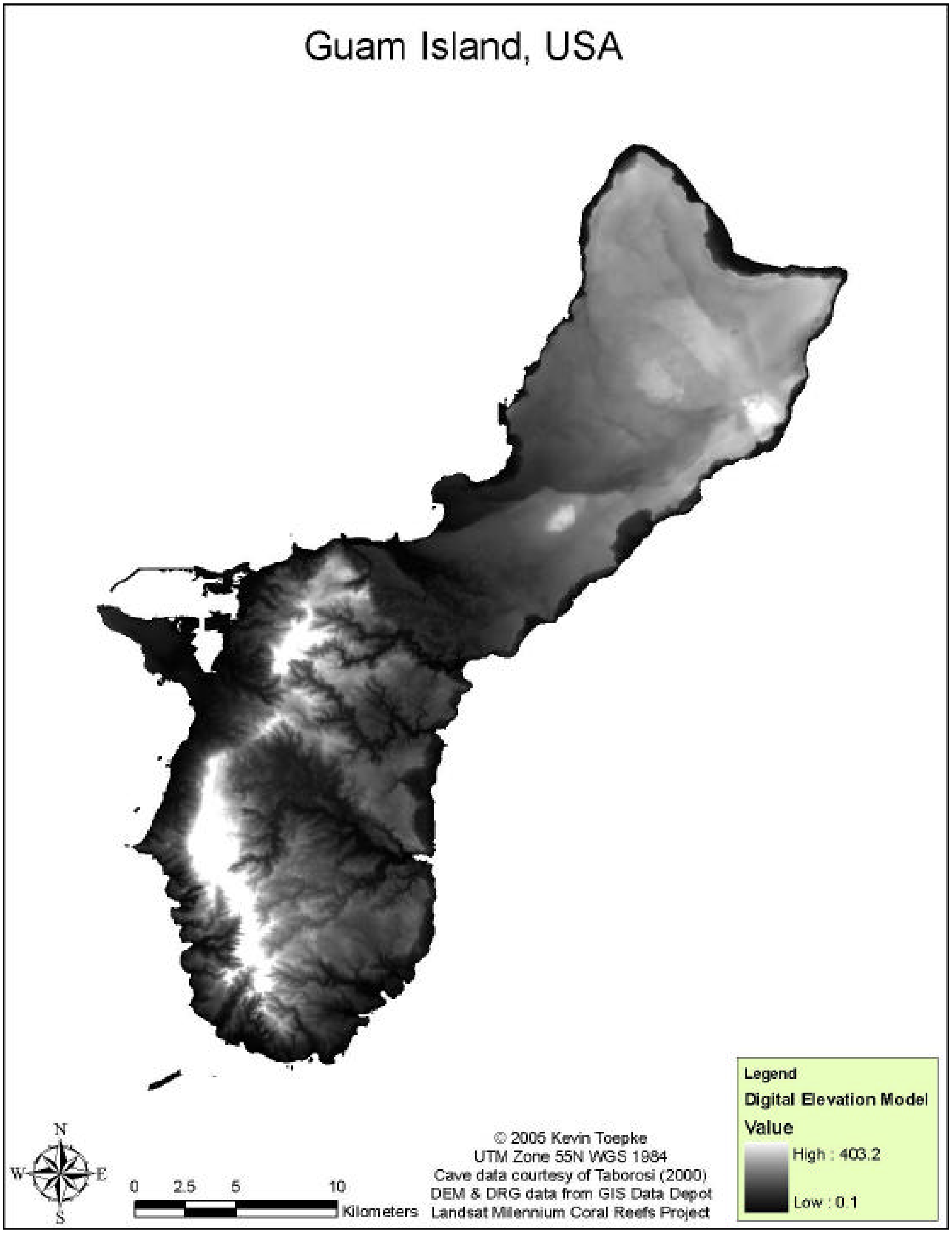


Figure 46: Digital Elevation Model (DEM) of Guam Island

Figure 47: Hillshade of Guam generated from the DEM of Guam Island

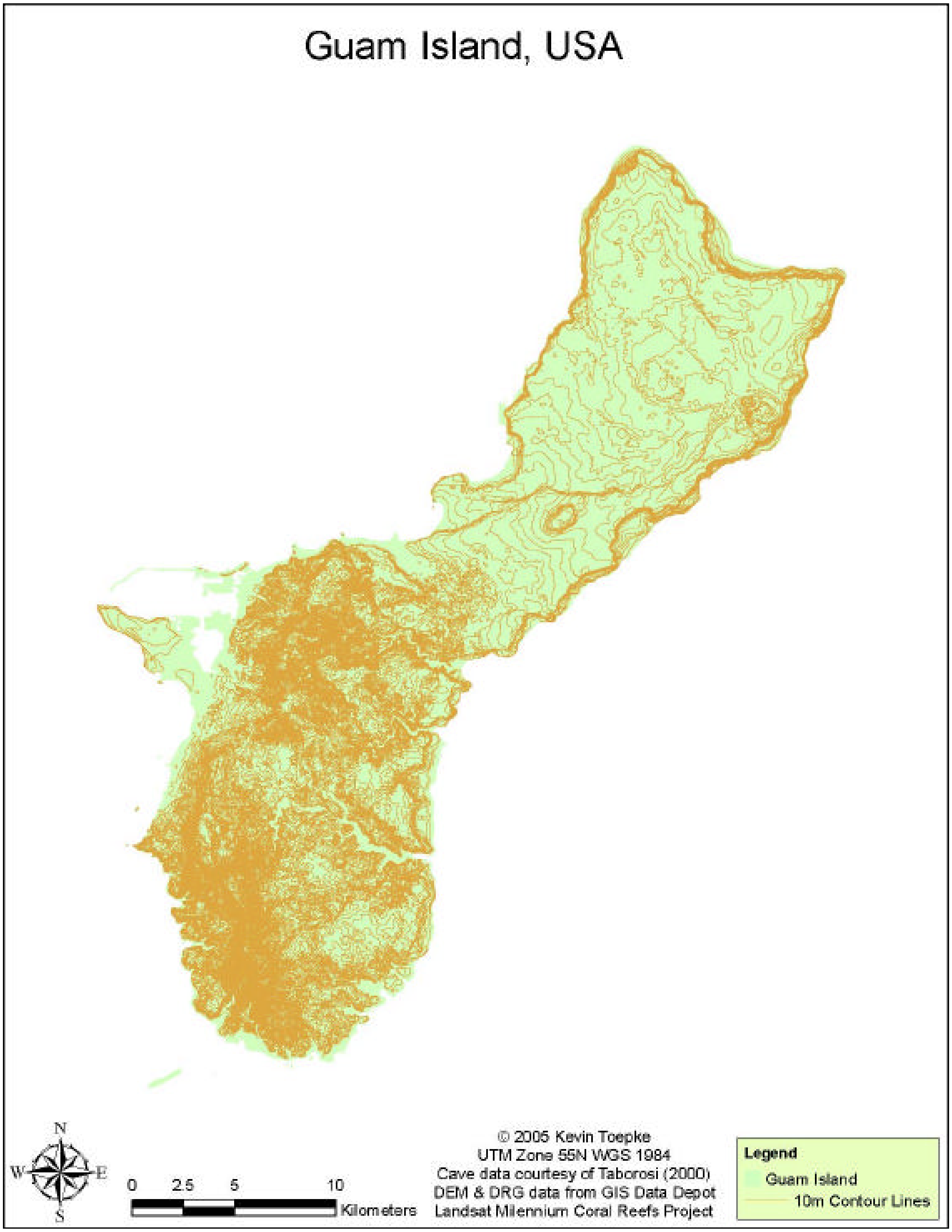


Figure 48: Map of Guam Island with island outline and 10m contour lines generated from the DEM of Guam Island

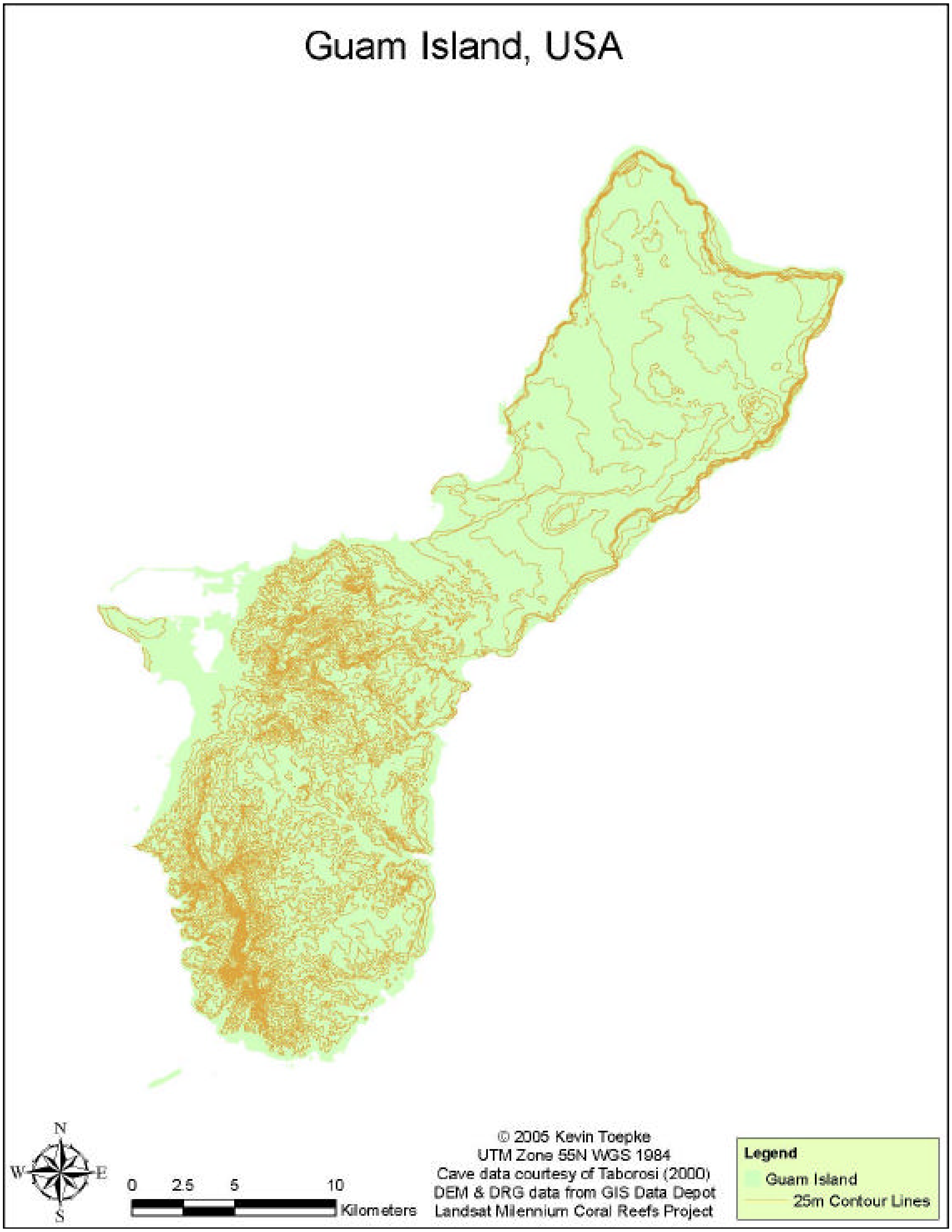


Figure 49: Map of Guam Island with island outline and 25m contour lines generated from the DEM of Guam Island

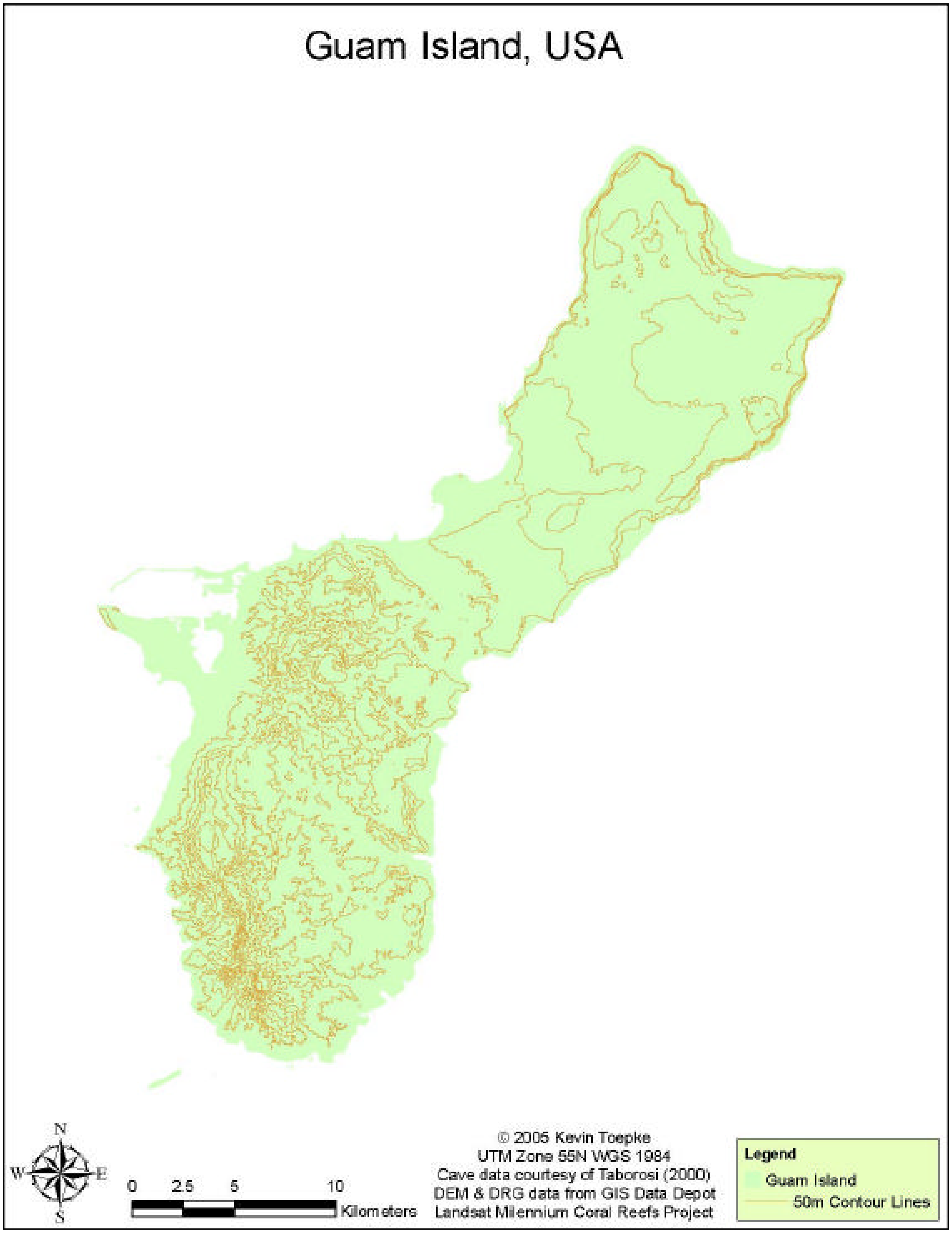


Figure 50: Map of Guam Island with island outline and 50m contour lines generated from the DEM of Guam Island

A Digital Raster Graphic (DRG) of Guam was acquired from USGS (2001r). The DRG was first converted to Erdas Imagine's Image format in Erdas Imagine then reprojected to WGS 1984 UTM Zone 55N using ArcToolbox, then finally loaded into the ArcMap document for Guam (Figure 51) and georectified to the LANDSAT image using the Reference tool within the Georeferencing toolbar in ArcMap.

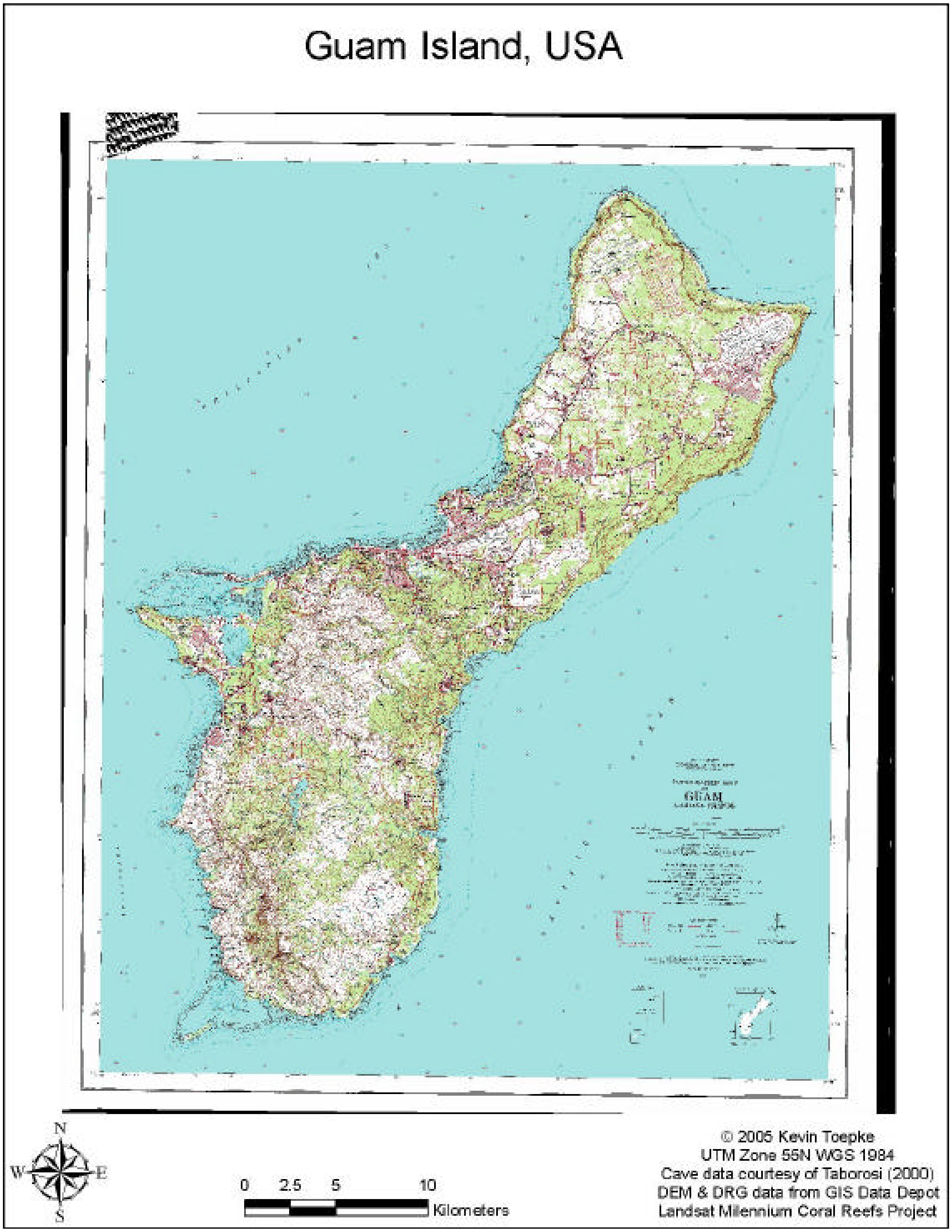


Figure 51: Map of Guam Island showing Digital Raster Graphics (DRG) Layer

Finally, two ArcScene documents were produced for visualization purposes. One with the true-color LANDSAT scene draped over the DEM (Figure 52) and one with the DRG draped over the DEM (Figure 53). In both cases, the appropriate image and the DEM were brought into ArcScene and the vertical exaggeration factor of the images were set to the five times the elevation from the DEM.

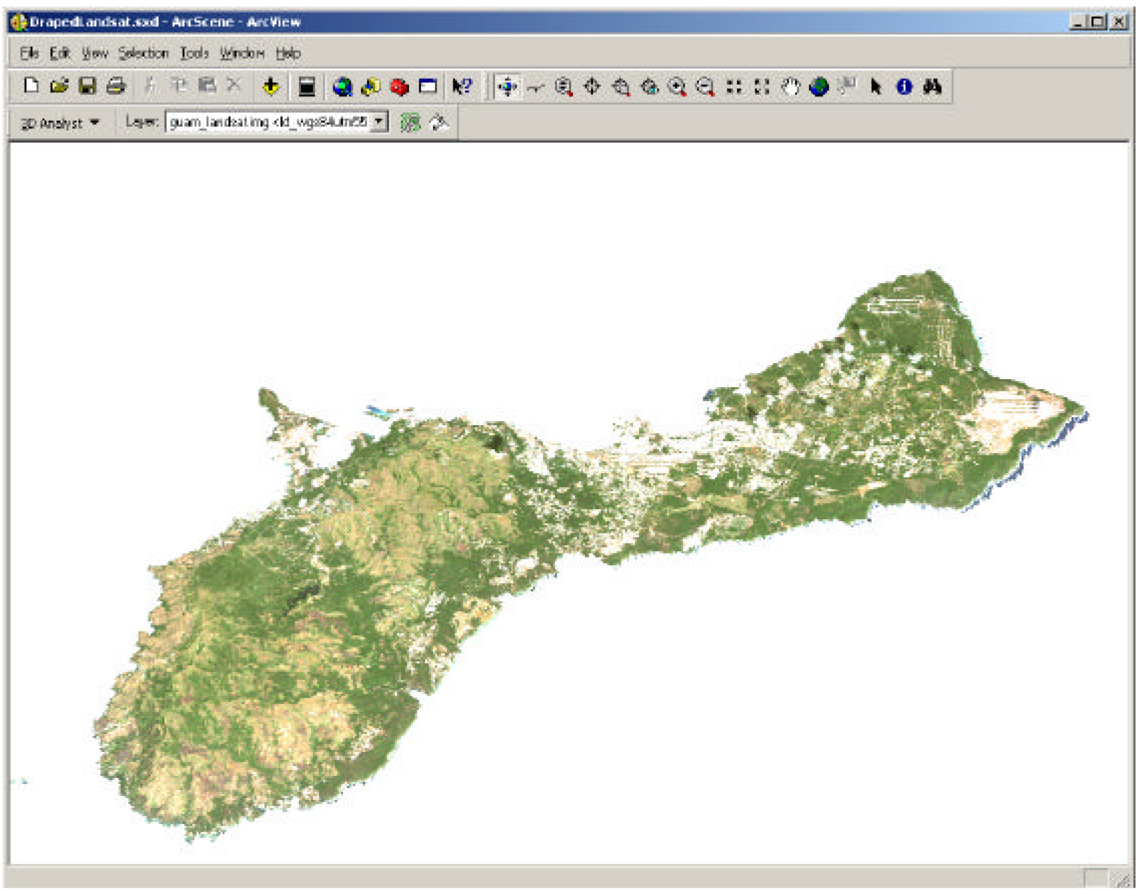


Figure 52: ArcScene of Guam's LANDSAT scene draped over the DEM with 5x vertical exaggeration

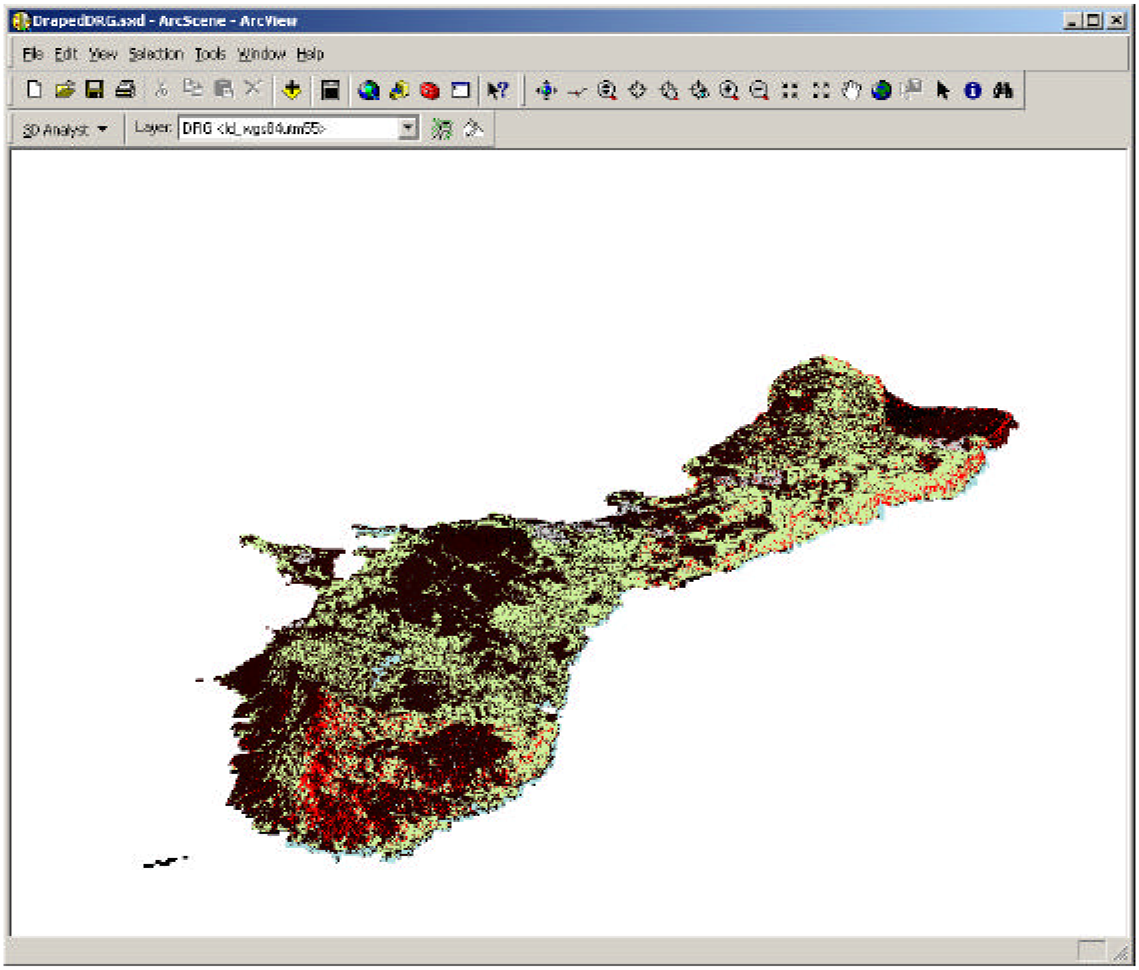


Figure 53: ArcScene of Guam's DRG draped over the DEM with 5x vertical exaggeration

Aguijan

Stafford (2003) cataloged the cave and karst features of Aguijan as part of the requirements for his Masters of Science degree from the Mississippi State University Department of Geosciences. It contains general locations and descriptions of the mapped karst features of Aguijan broken down by cave type and physiographic province. The reduced survey data in Walls format, with location information; working cave maps in XaraX format; and final cave maps in JPEG format were received via personal communication with Stafford.

Once acquired, the data were initially split into directories, one for each cave. After the data were organized into separate directories for each cave, a vetting process took place to correctly identify each cave's type and physiographic province. The location data retrieved from the Walls files and the descriptions were used to vet the physiographic province information, and the cave maps and descriptions were used to vet the cave types. No inconsistencies in cave type or physiographic province were found across the data sources. The organized data for Aguijan are summarized in Appendix A.

After the data were vetted, a directory was created for the island, subdirectories were created for each physiographic province, and further subdirectories were created for each cave type. Then the cave directories were moved to the correct cave type subdirectory.

When the data were organized a series of HTML pages was created, one for each feature. The HTML page was created in the directory for the feature. The HTML pages contain the cave descriptions and cave maps from Stafford (2003) as well as links to the Walls line plots and the XaraX working map files, if available.

The data were then loaded into a Microsoft Excel spreadsheet for easy manipulation. Once basic cleaning of the data had occurred, the data were then loaded into the Microsoft Access GDB using the import table command. The http_page_location field was then updated to the correct directory name using a SQL update statement. Once the data were in the GDB and fully populated, one layer file was created for each combination of cave type and physiographic province that exists in the GDB. The layer files were created in ArcCatalog and use a SQL query to pull information on the appropriate cave or karst features from the GDB. These layer files were then loaded into an ArcMap document for Aguijan. Once in ArcMap, the display properties were modified to support hyperlinks based on the http_page_location field in the CAVES table, and the label properties were modified to label each feature using the name field in the CAVES table. Finally the symbology was changed to use a different symbol for each physiographic province and a different color for each cave type within physiographic province (Figure 59).

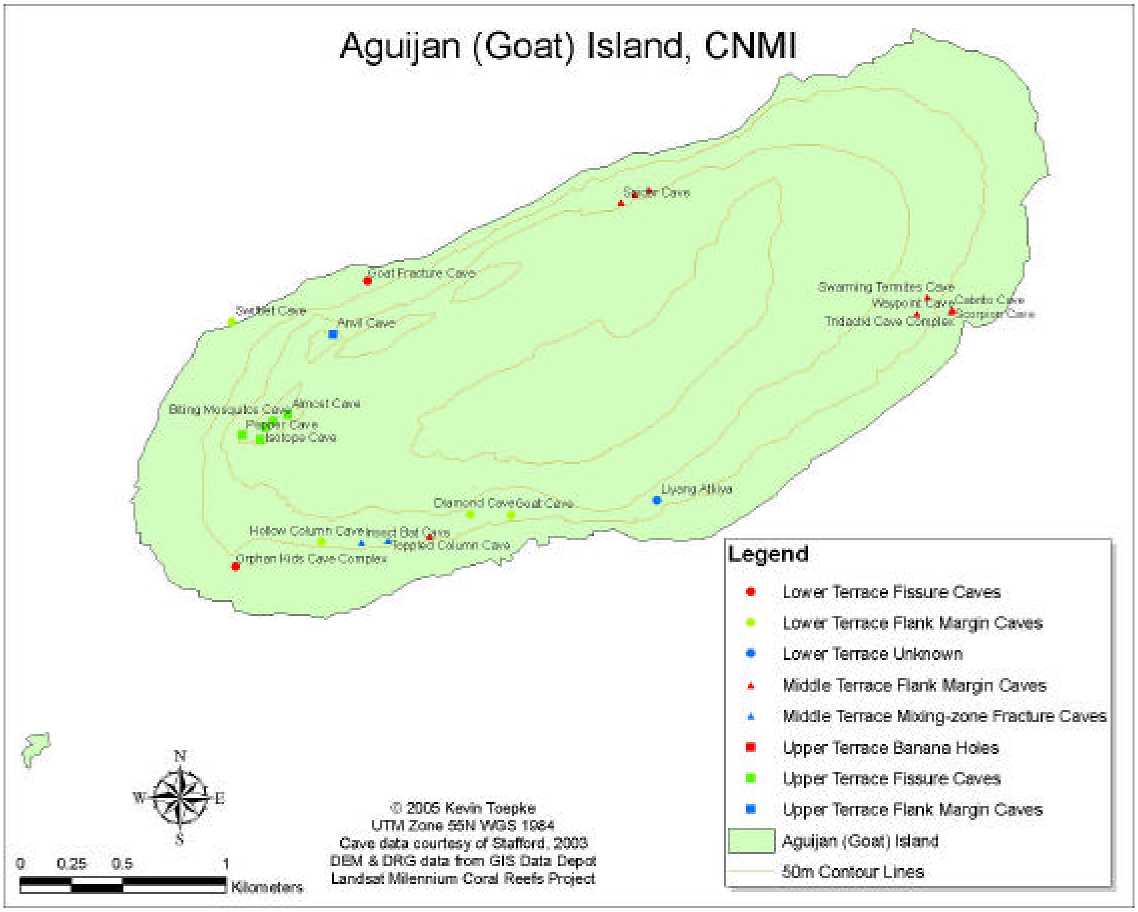


Figure 54: Map of Aguijan with Cave Layers and Island Outline

The LANDSAT-7 scene that covers Aguijan is Path 100, Row 50. The Millennium Coral Reef Project had scenes from two dates, 08/17/1999 (NASA, 2005c) and 03/15/2001 (NASA, 2005d), only the 2001 scene had less than 5% cloud cover. Erdas Imagine was used to stack the multiple source image files into a multi-layer image file. Once complete, the scene was subsetted using a rectangular area of interest in Erdas Imagine to include just a small area around the island of Aguijan. The subsetted 2001 scene was twice loaded into the ArcMap document (Figure 55 & Figure

56). The symbology on one of the scenes was changed to true-color (Band-1 to blue, Band-2 to green, Band-3 to red), and the other had its symbology changed to false-color IR (Band-2 to blue, Band-3 to green, Band-4 to red).

Figure 55: True Color LANDSAT-7 Image of Aguijan Island

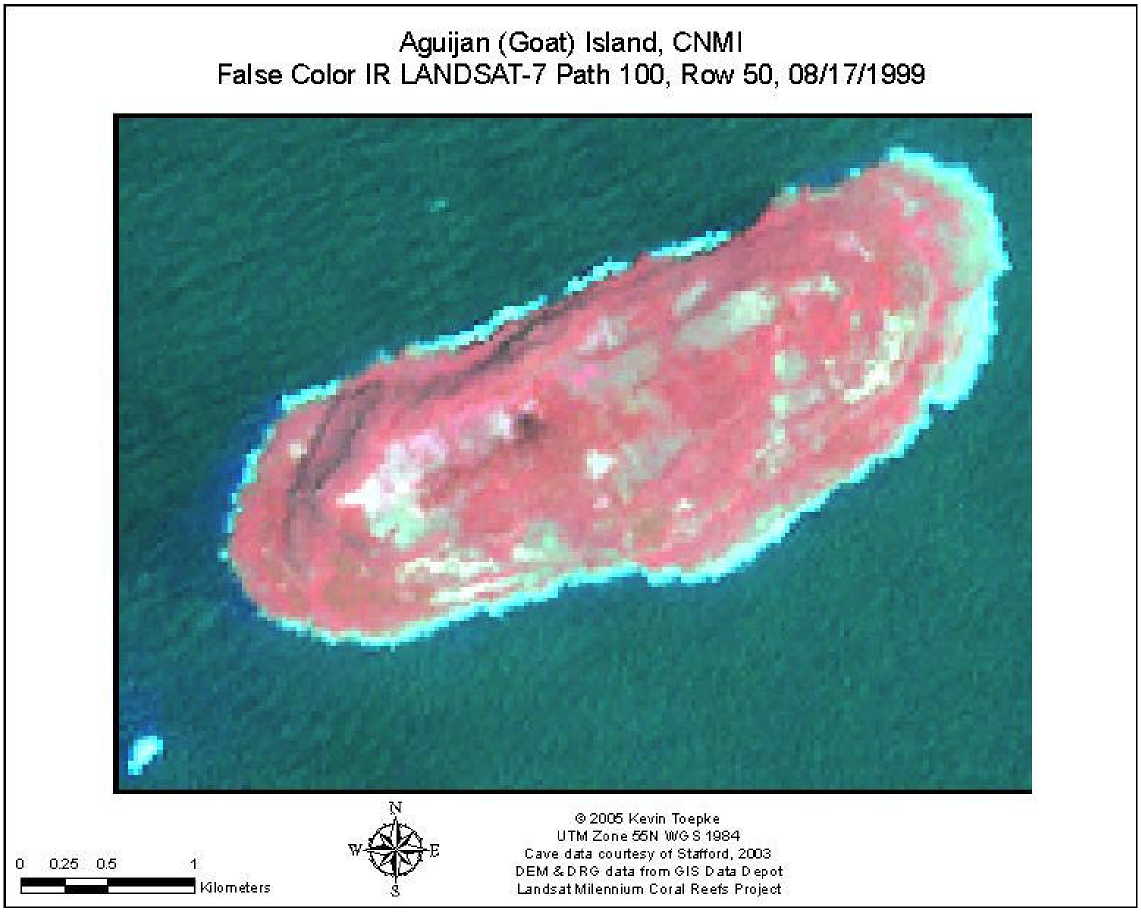


Figure 56: False Color IR LANDSAT-7 Image of Aguijan Island

Digital Elevation Models for Aguijan in the SDTS format were acquired from USGS (2001a). These DEM was converted into GRID format using the sdts2grid program and reprojected to WGS 1984 UTM Zone 55N. The DEM was then loaded into the ArcMap document for Aguijan (Figure 57) Upon loading the DEM into ArcMap, it was found that the DEM also needed to be georectified to the LANDSAT image. This was done using the Reference option in the Georeference toolbar in ArcMap. The

LANDSAT image was chosen as truth because it more accurately lined up with the cave locations than the DEM.

Once the DEM was georectified the following computations were made on the DEM in Spatial Analyst: hillshade document (Figure 58), 10-m contour lines (Figure 59), 25-m contour lines (Figure 60), 50-m contour lines (Figure 61). The contour lines were computed by using the contour option within Spatial Analyst, hillshade using the Hillshade option, and island outline was computed by using Raster Calculator to set all elevations less than or equal to zero to zero and all elevations greater than zero to one then converting the resulting grid data to a polygon using the Export Raster to Feature option in Spatial Analyst. Once the contour and island outline calculations were complete, the results were imported into the geodatabase using ArcCatalog's Import Feature Class (single) command. The resulting feature classes were then added to the ArcMap for Aguijan and the symbology was changed to contour for the contour lines and a fill-color of green for the Island Outline.

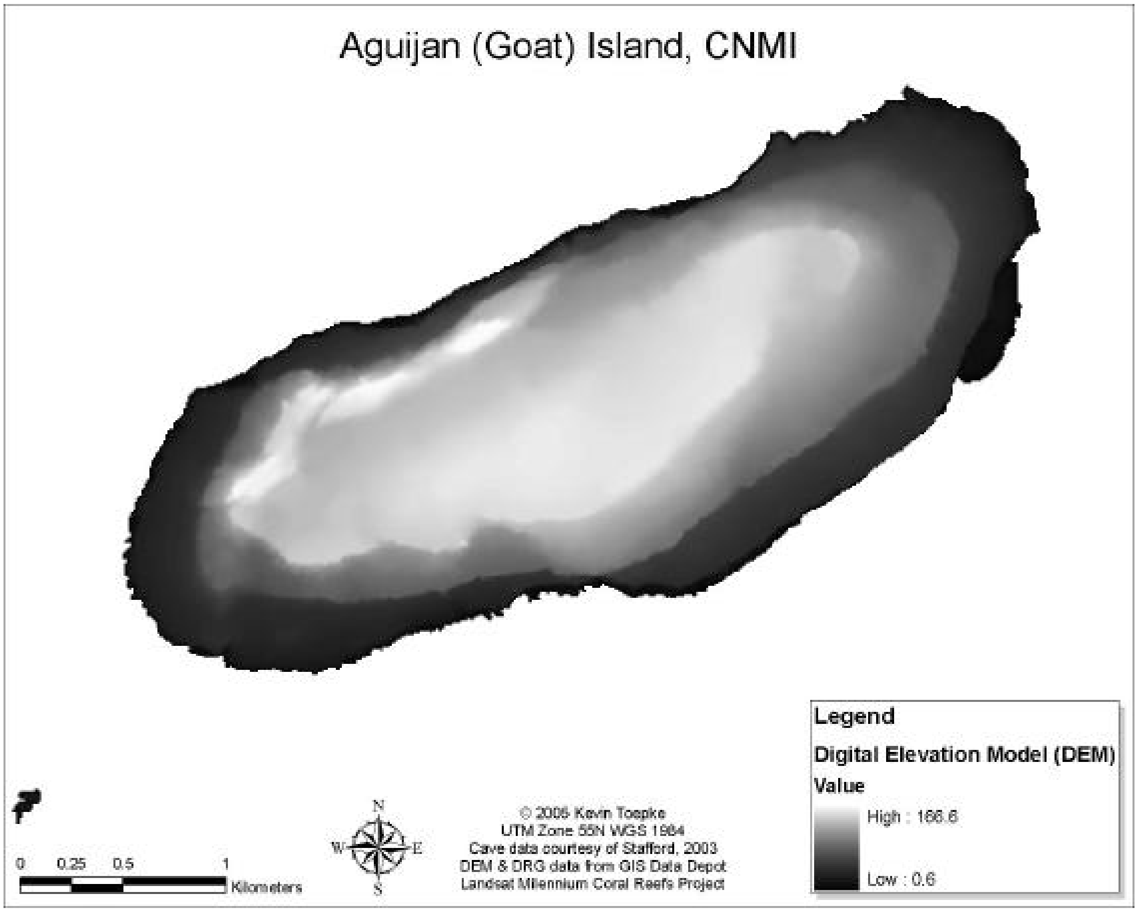


Figure 57: Digital Elevation Model (DEM) of Aguijan Island

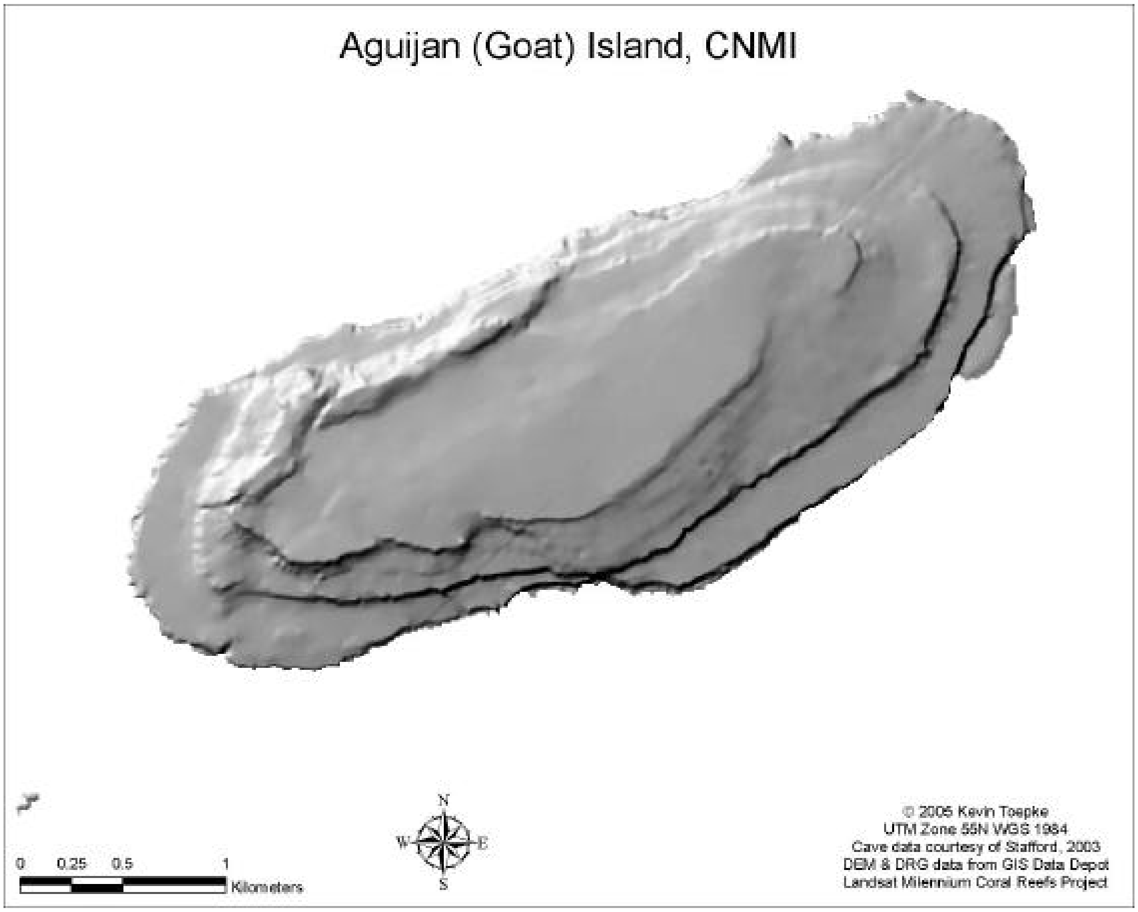


Figure 58: Hillshade of Aguijan generated from the DEM of Aguijan Island

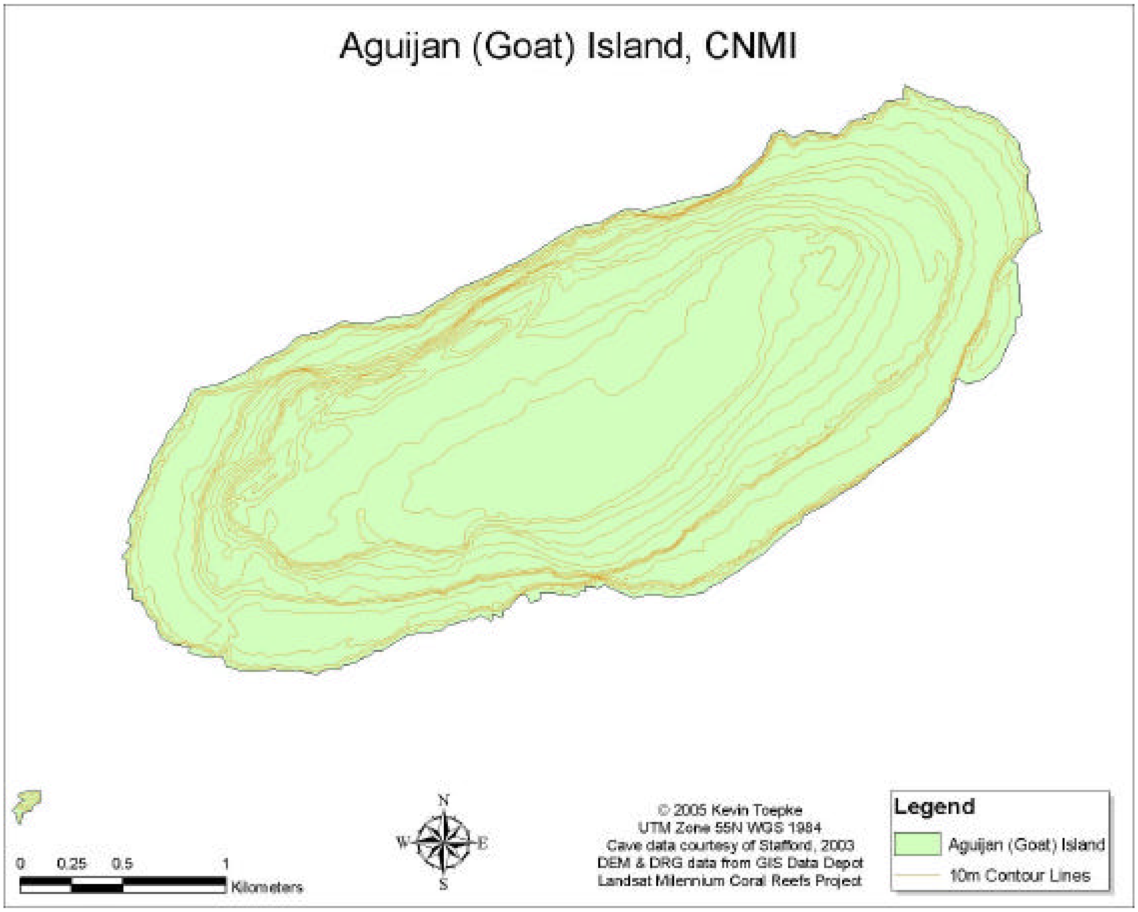


Figure 59: Map of Aguijan Island with island outline and 10m contour lines generated from the DEM of Aguijan Island

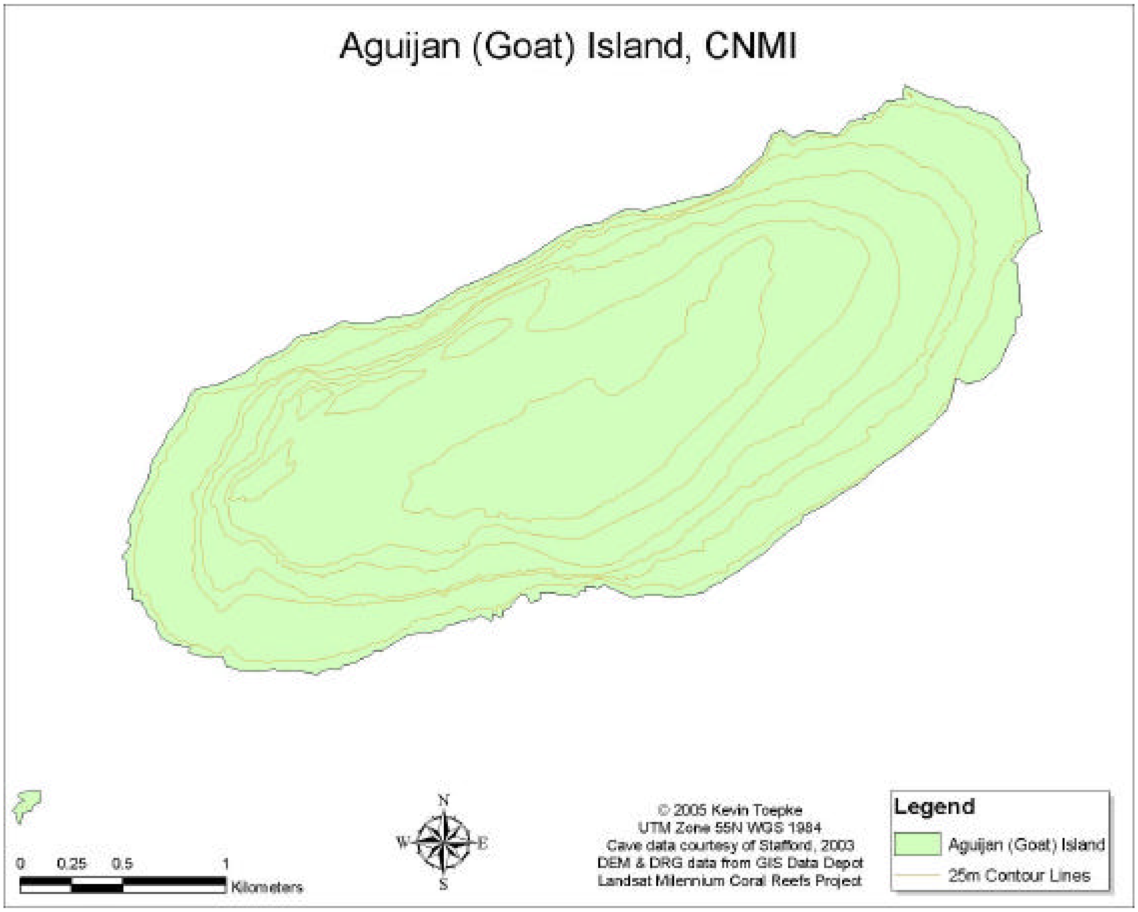


Figure 60: Map of Aguijan Island with island outline and 25m contour lines generated from the DEM of Aguijan Island

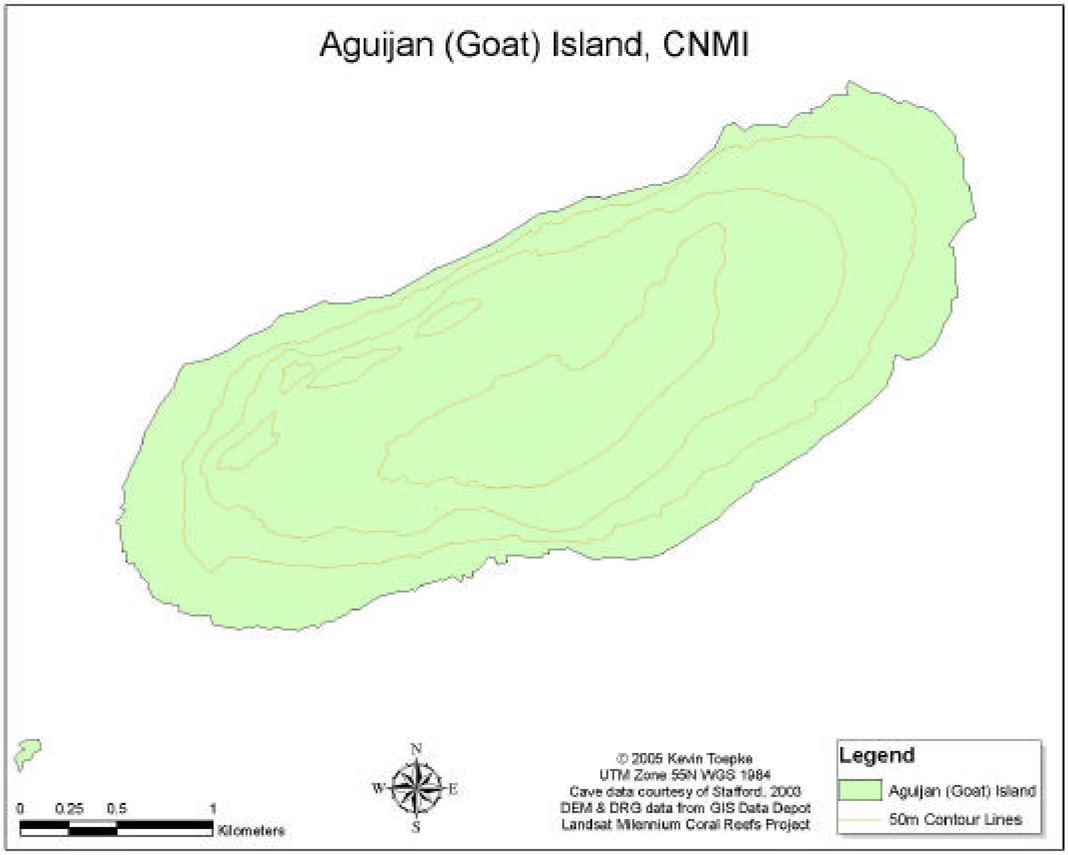


Figure 61: Map of Aguijan Island with island outline and 50m contour lines generated from the DEM of Aguijan Island

A Digital Raster Graphic (DRG) of Tinian and Aguijan was acquired from USGS (2001r). The DRG was first converted to Erdas Imagine's Image format in Erdas Imagine then reprojected to WGS 1984 UTM Zone 55N using ArcToolbox, then finally loaded into the ArcMap document for Aguijan (Figure 62) and georectified to the LANDSAT image using the Reference tool within the Georeferencing toolbar in ArcMap.

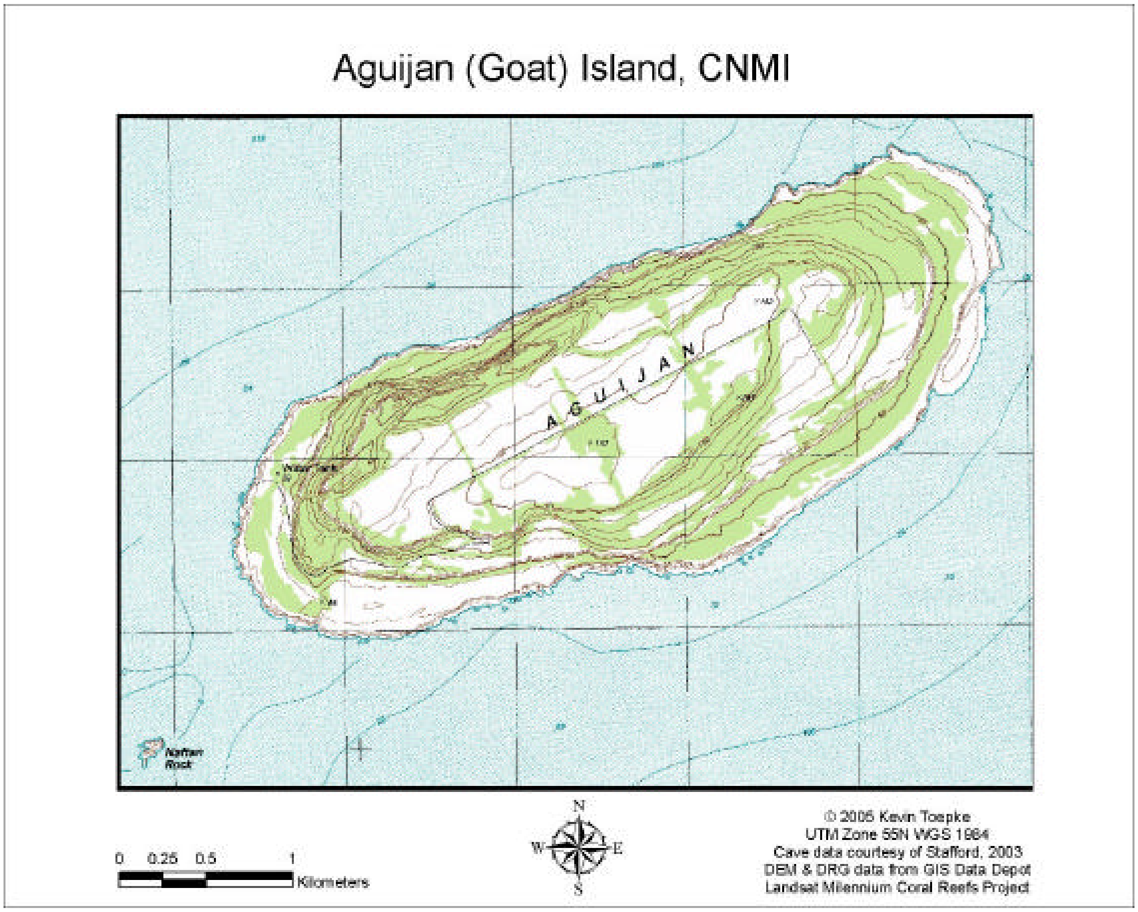


Figure 62: Map of Aguijan Island showing Digital Raster Graphics (DRG) Layer

Finally, two ArcScene documents were produced for visualization purposes. One with the true-color LANDSAT scene draped over the DEM (Figure 63) and one with the DRG draped over the DEM (Figure 64). In both cases, the appropriate image and the DEM were brought into ArcScene and the vertical exaggeration factors were set to five times the elevation from the DEM.

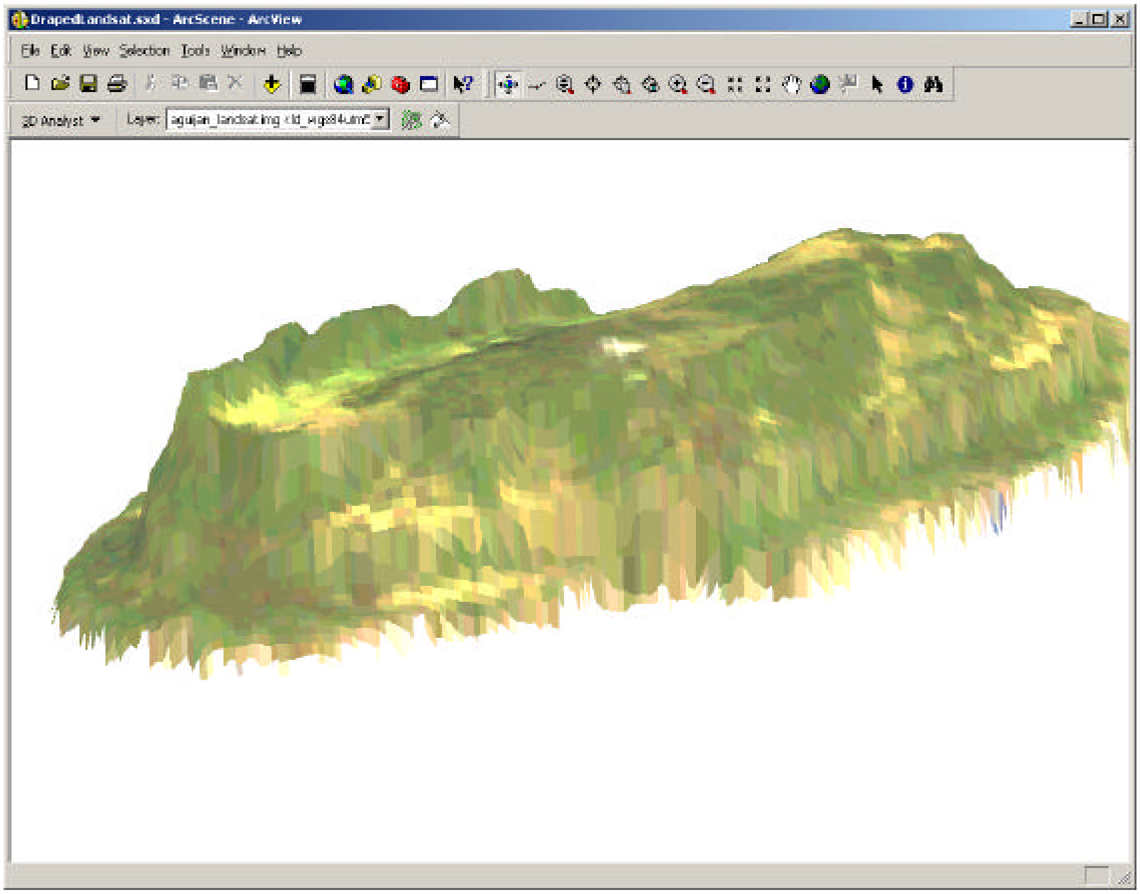


Figure 63: ArcScene of Aguijan's LANDSAT scene draped over the DEM with 5x vertical exaggeration

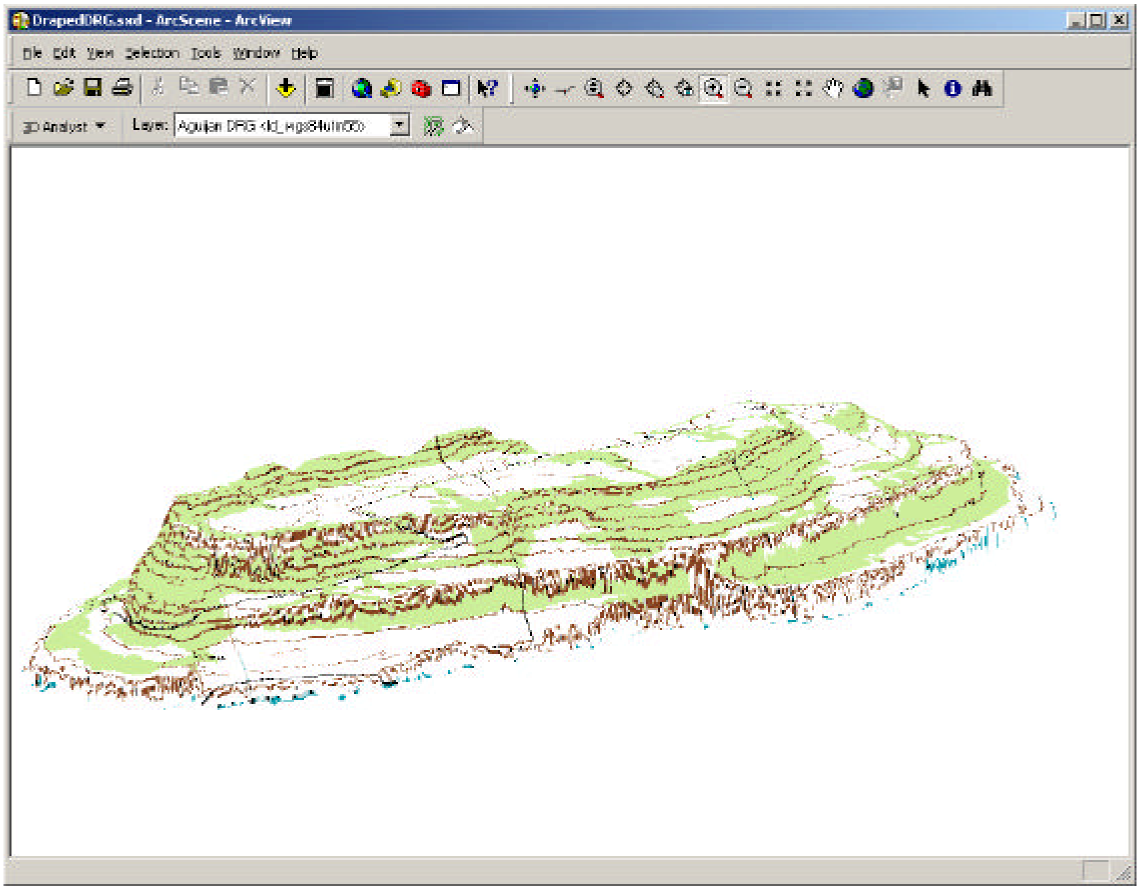


Figure 64: ArcScene of Aguijan's DRG draped over the DEM with 5x vertical exaggeration

Saipan

Wexel (in progress) cataloged the cave and karst features of Saipan as part of the requirements for his Masters of Science degree from the University of Guam. As of this writing, the author has not received any data on the caves and karst of Saipan. However, 4 cave maps were received from Mylroie via personal communication. Locations for three of the caves (*Kalabera* Cave, *I Madog*, and Ladder Beach Caves) were identified using Cloud et al (1956). No location information was available for Hourglass Cave.

Once acquired, the data were initially split into directories, one for each cave. After the data were organized into separate directories for each cave, a vetting process took place to correctly identify each cave's type and physiographic province. The organized data are summarized in Appendix D.

After the data was organized a directory was created for the island, subdirectories were created for each physiographic province, and further subdirectories were created for each cave type. Then the cave directories were moved to the correct cave type subdirectory.

When the data were organized a series of HTML pages was created, one for each feature. The HTML page was created in the directory for the feature. The HTML pages contain the cave maps from Mylroie. The data were then manually entered into the Microsoft Access GDB. Once the data were in the GDB and fully populated, one layer file was created for each combination of cave type and physiographic province that exists in the GDB. The layer files were created in ArcCatalog and use a SQL query to pull information on the appropriate cave or karst features from the GDB. These layer files were then loaded into an ArcMap document for Saipan. Once in ArcMap, the display properties were modified to support hyperlinks based on the http_page_location field in the CAVES table, and the label properties were modified to label each feature using the name field in the CAVES table. Finally the symbology was changed to use a different symbol for each physiographic province and a different color for each cave type within physiographic province (Figure 59).

The non-karst data were included in this study in order to provide as much of the same "one-stop-shopping" for data as possible for Saipan.

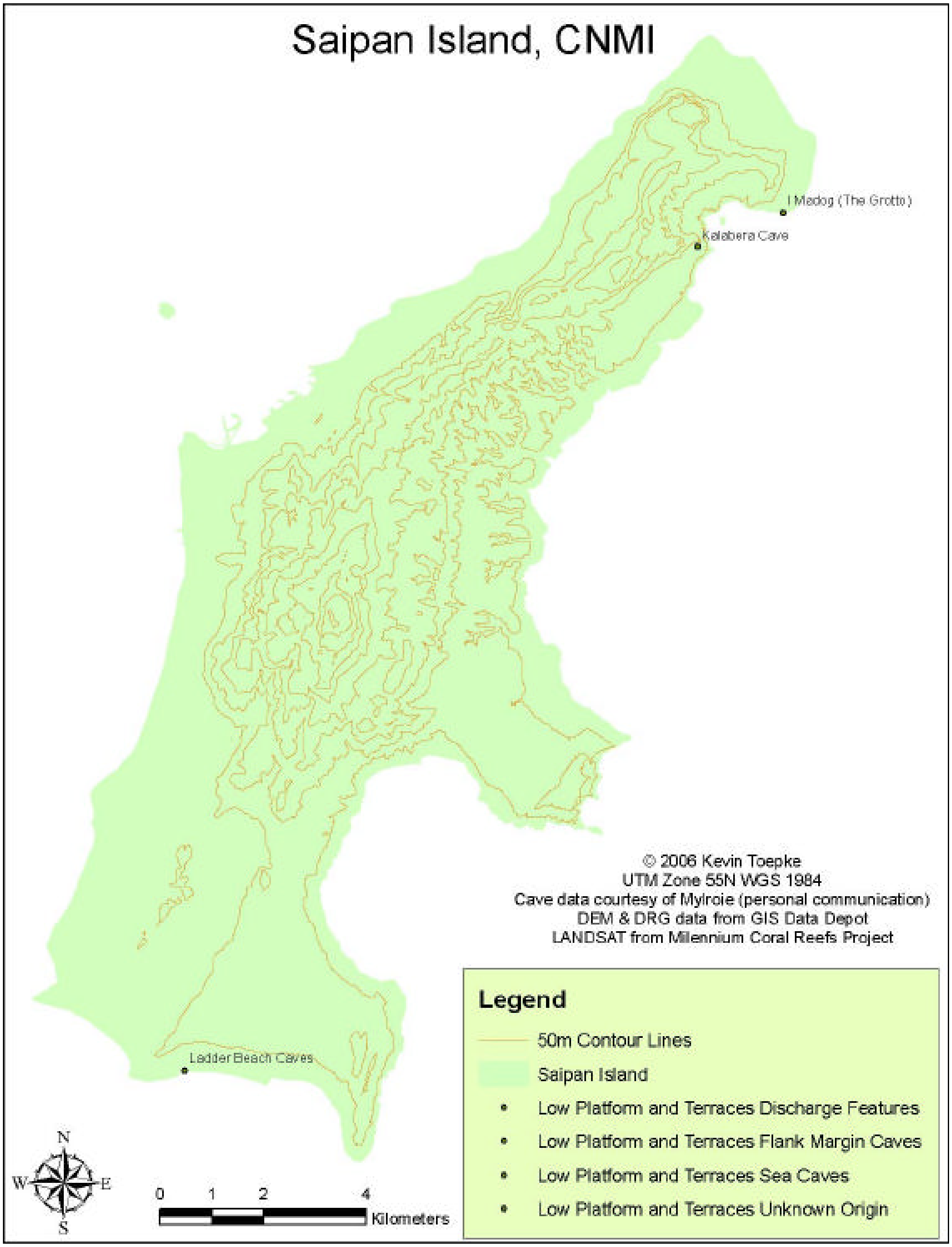


Figure 65: Map of the cave locations on Saipan Island, CNMI

The LANDSAT-7 scenes that cover Saipan are Path 100, Row 49 and Path 100, Row 50. The Millennium Coral Reef Project had Path 100, Row 49 scenes from three dates, 08/17/1999 (NASA, 2005a), 02/25/2000, and 10/26/2001; and Path 100, Row 50 scenes from two dates, 08/17/1999 (NASA, 2005c) and 03/15/2001 (NASA, 2005d). Only the 2001 Path 100, Row 50 scene had less than 20% cloud cover, and only the 1999 Path 100, Row 49 scene had less than 10% cloud cover. Erdas Imagine was used to first stack the multiple source image files into multi-layer image file, one per scene, and then merge the two scenes into one complete image of Saipan, using the 2001 Path 100, Row 50 where overlap occurred because of less cloud cover in the overlap area. Once complete, the scene was subsetted using a rectangular area of interest in Erdas Imagine to include just a small area around the island of Saipan. The subsetted 2001 scene was twice loaded into the ArcMap document (Figure 66 & Figure 67). The symbology on one of the scenes was changed to true-color (Band-1 to blue, Band-2 to green, Band-3 to red), and the other had its symbology changed to false-color IR (Band-2 to blue, Band-3 to green, Band-4 to red).

Figure 66: True Color LANDSAT-7 Image of Saipan Island

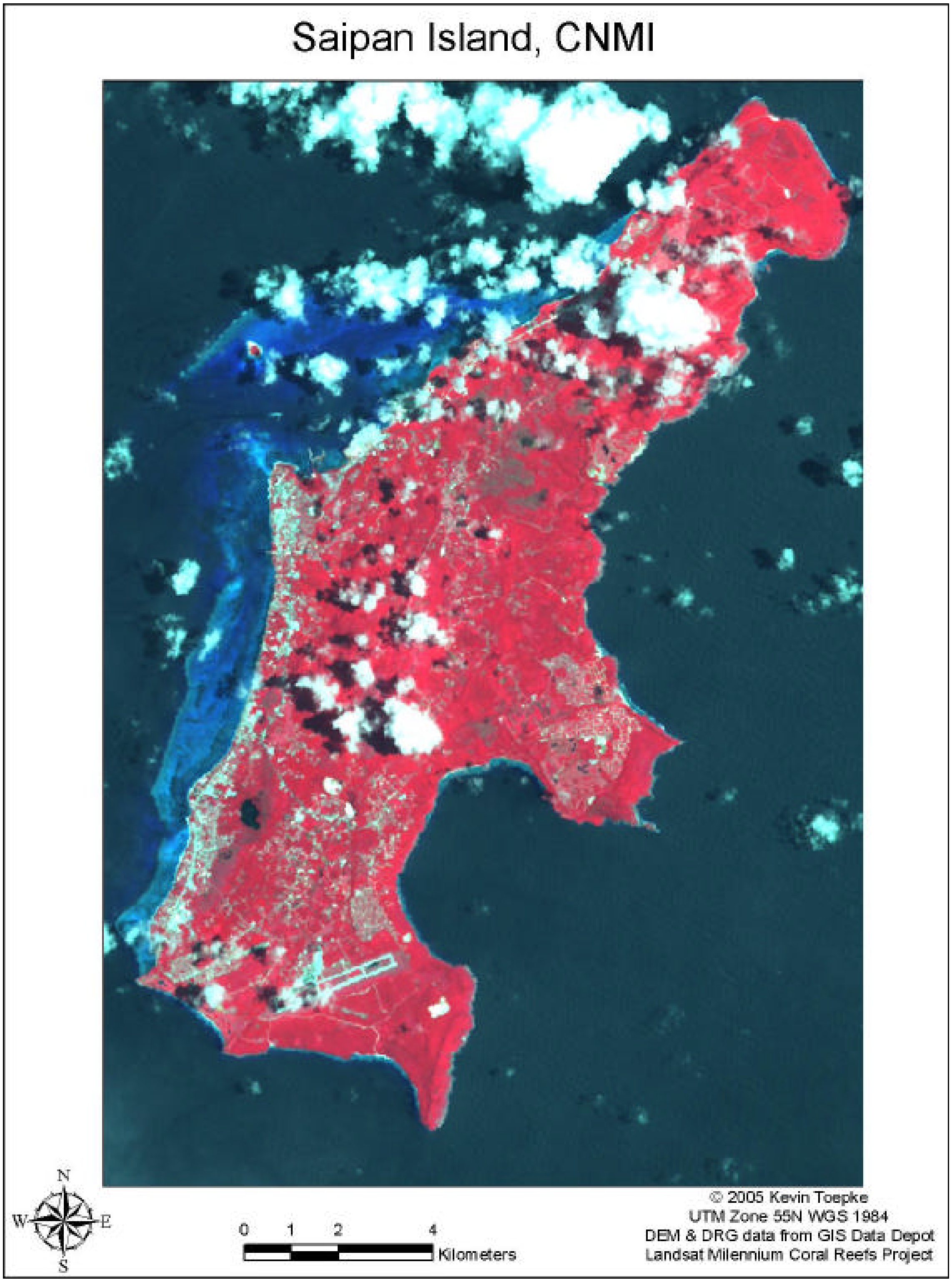


Figure 67: False Color IR LANDSAT-7 Image of Saipan Island

Digital Elevation Models for Saipan in the SDTS format were acquired from USGS (2001d). This DEM was converted into GRID format using the sdts2grid program and reprojected to WGS 1984 UTM Zone 55N. The DEM was then loaded into the ArcMap document for Saipan (Figure 68) Upon loading the DEM into ArcMap it was found that the DEM also needed to be georectified to the LANDSAT image. This was done using the Reference option in the Georeference toolbar in ArcMap. The LANDSAT image was chosen as truth because it more accurately lined up with the cave locations than the DEM.

Once the DEM was georectified the following computations were made on the DEM in Spatial Analyst: hillshade document (Figure 69), 10-m contour lines (Figure 70), 25-m contour lines (Figure 71), 50-m contour lines (Figure 72). The contour lines were computed by using the contour option within Spatial Analyst, hillshade using the Hillshade option, and island outline was computed by using Raster Calculator to set all elevations less than or equal to zero to zero and all elevations greater than zero to one then converting the resulting grid data to a polygon using the Export Raster to Feature option in Spatial Analyst. Once the contour and island outline calculations were complete, the results were imported into the geodatabase using ArcCatalog's Import Feature Class (single) command. The resulting feature classes were then added to the ArcMap for Saipan and the symbology was changed to contour for the contour lines and a fill-color of green for the Island Outline.

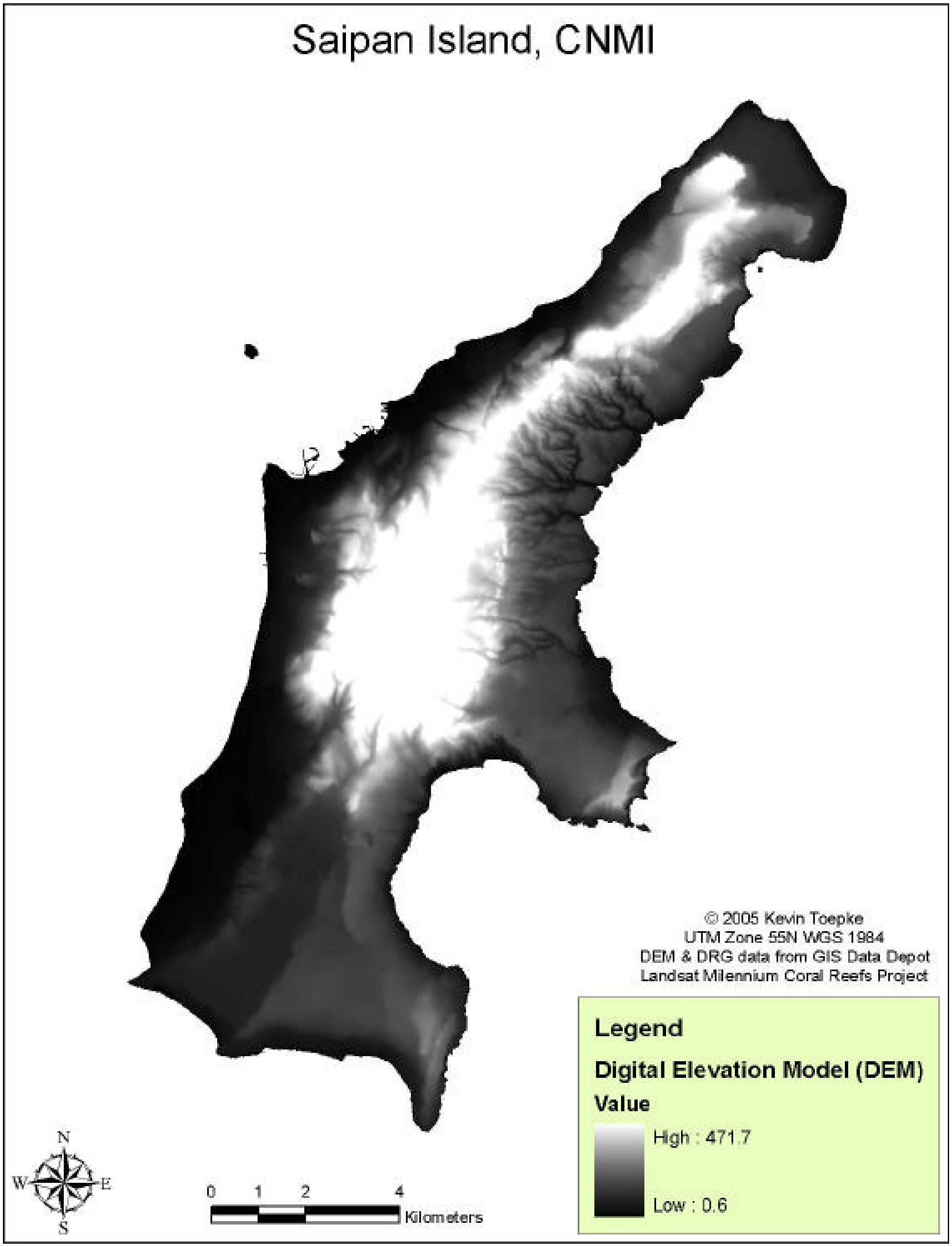


Figure 68: Digital Elevation Model (DEM) of Saipan Island

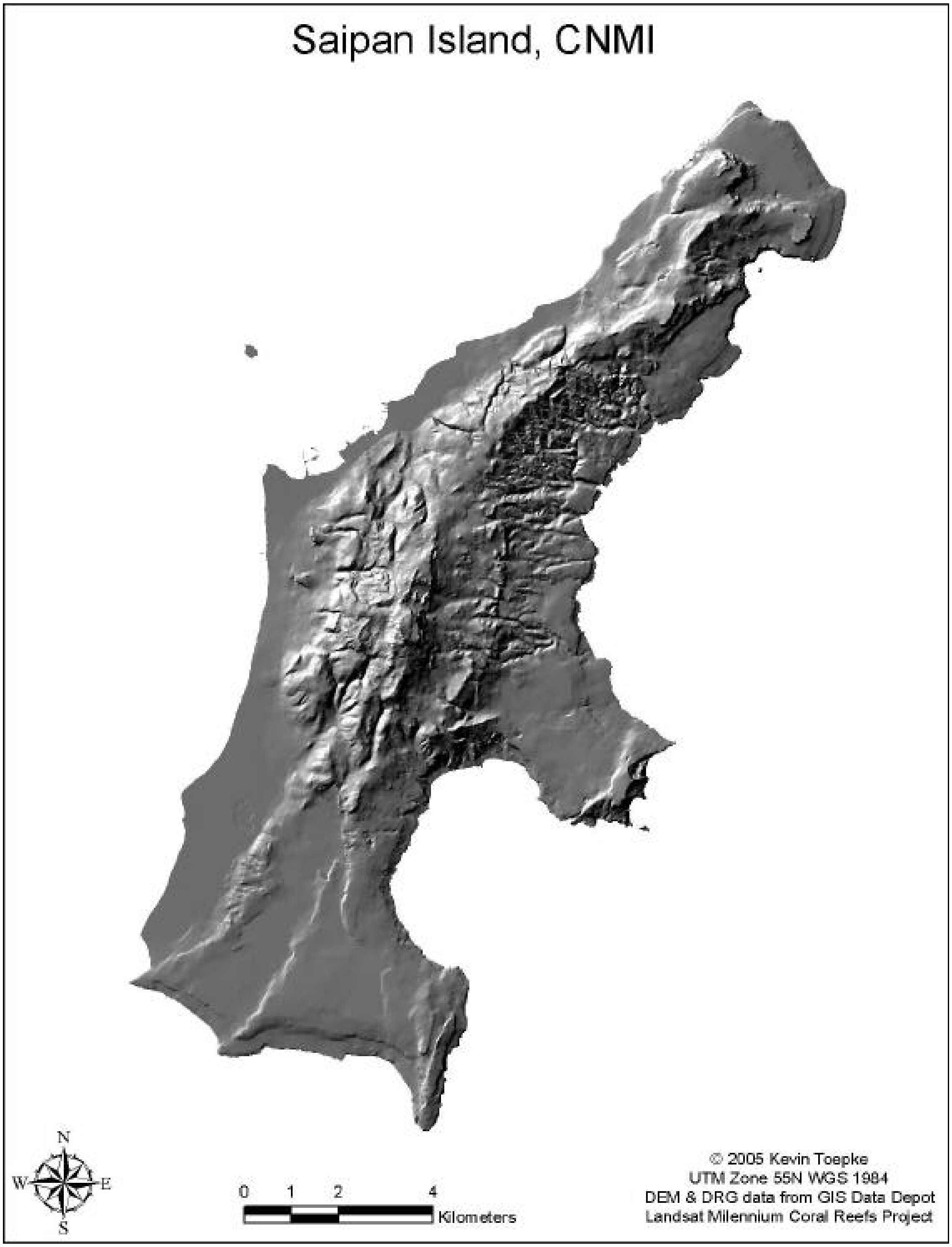


Figure 69: Hillshade of Saipan generated from the DEM of Saipan Island

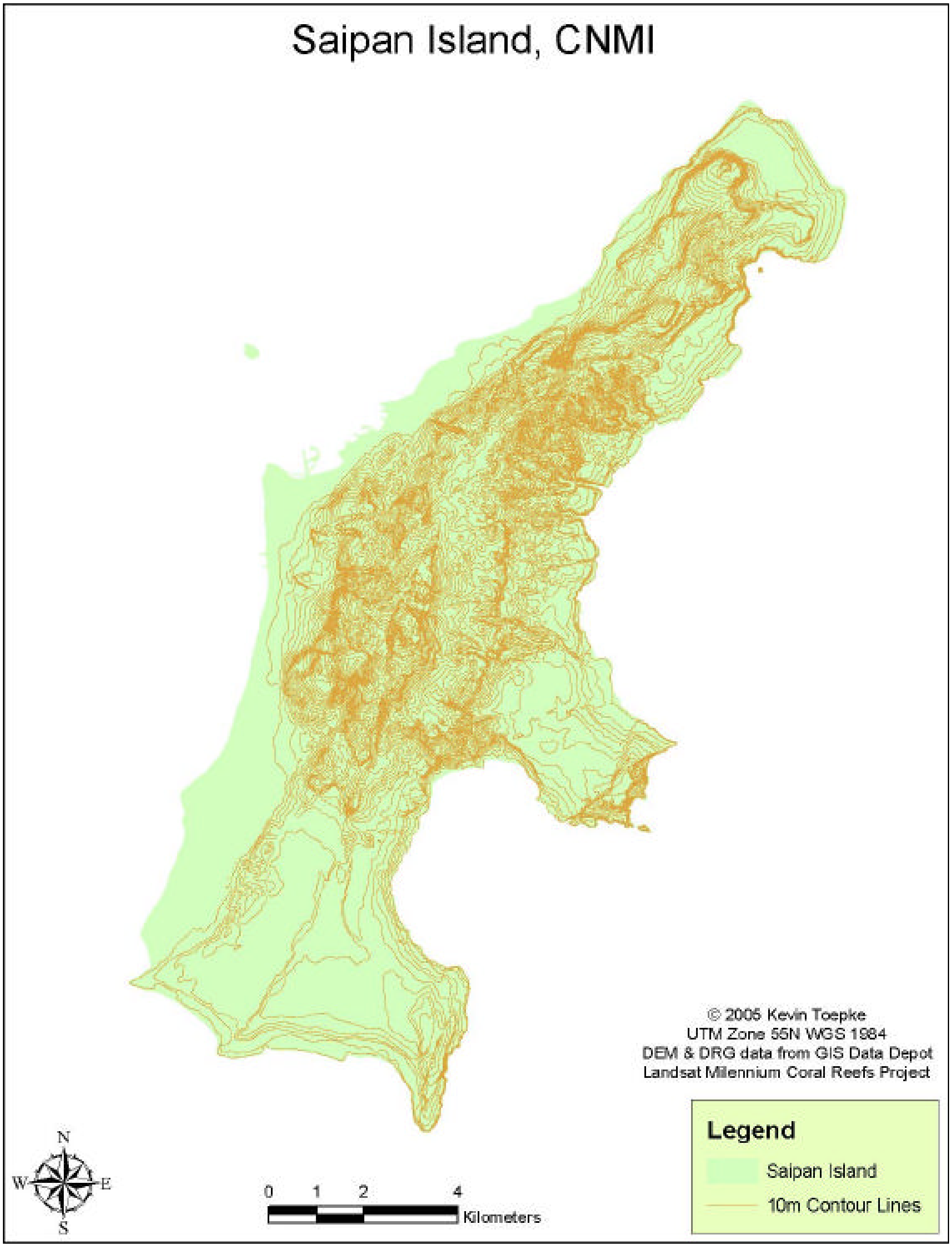


Figure 70: Map of Saipan Island with island outline and 10m contour lines generated from the DEM of Saipan Island

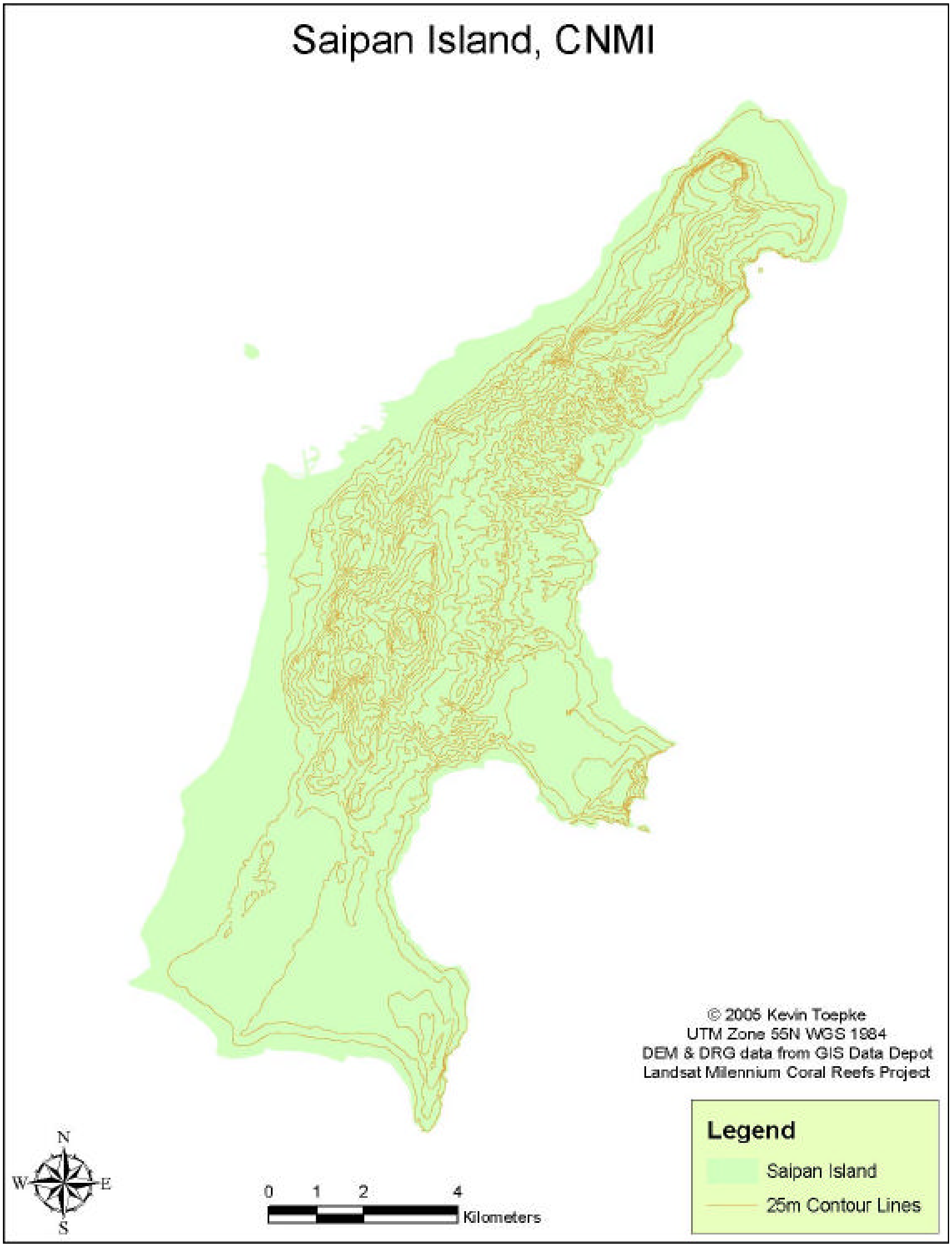


Figure 71: Map of Saipan Island with island outline and 25m contour lines generated from the DEM of Saipan Island

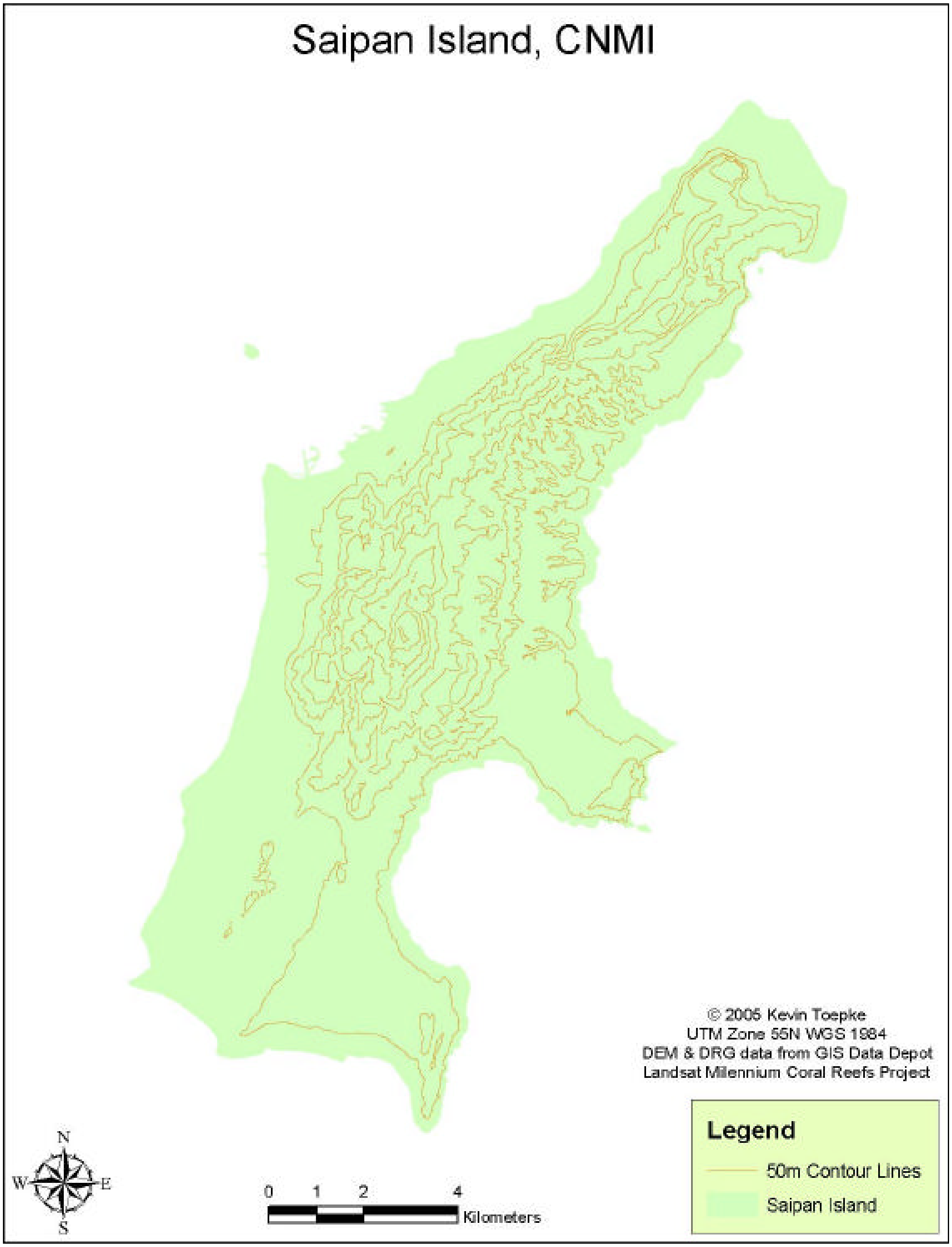


Figure 72: Map of Saipan Island with island outline and 50m contour lines generated from the DEM of Saipan Island

A Digital Raster Graphic (DRG) for Saipan was acquired from USGS (2001r). The DRG was first converted to Erdas Imagine's Image format in Erdas Imagine then reprojected to WGS 1984 UTM Zone 55N using ArcToolbox, then finally loaded into the ArcMap document for Saipan (Figure 73) and georectified to the LANDSAT image using the Reference tool within the Georeferencing toolbar in ArcMap.

Figure 73: Map of Saipan Island showing Digital Raster Graphics (DRG) Layer

Finally, two ArcScene documents were produced for visualization purposes. One with the true-color LANDSAT scene draped over the DEM (Figure 74) and one with the DRG draped over the DEM (Figure 75). In both cases, the appropriate image and the DEM were brought into ArcScene and the vertical exaggeration factors were set to the five times the elevation from the DEM.

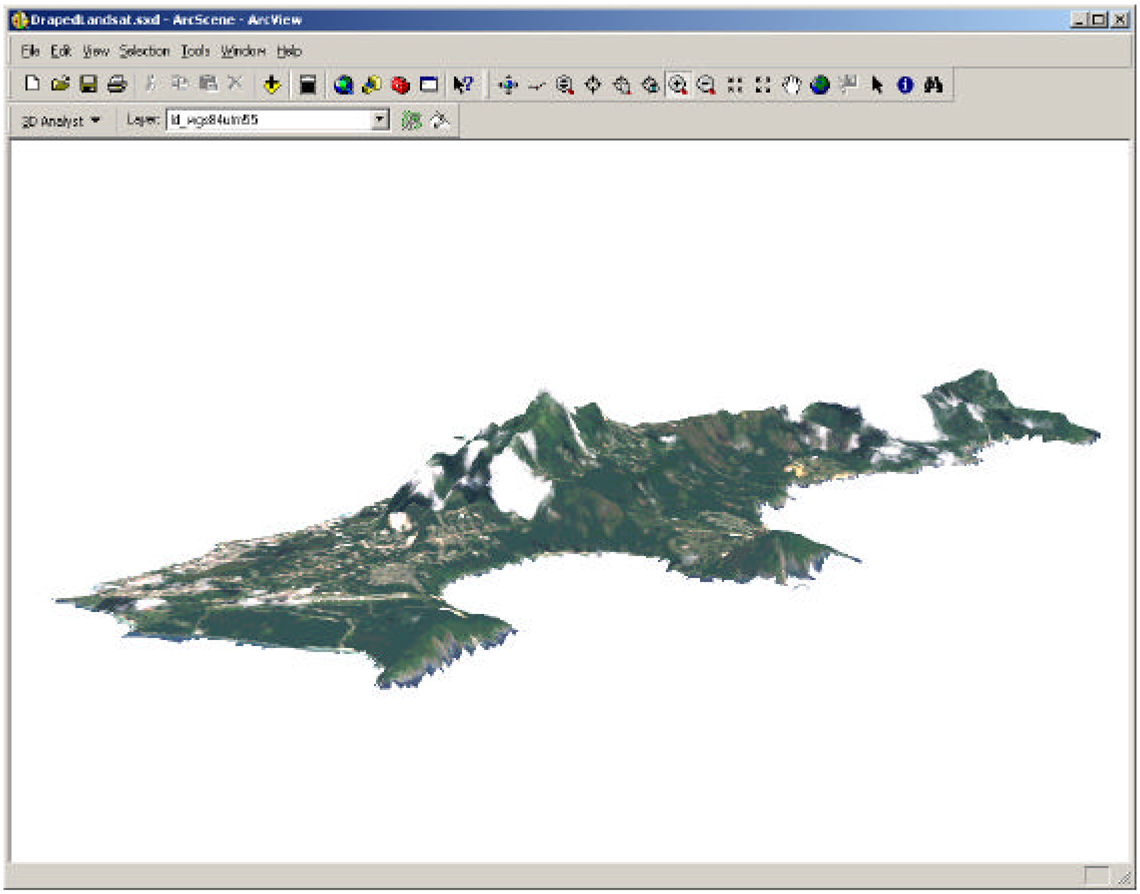


Figure 74: ArcScene of Saipan's LANDSAT scene draped over the DEM with 5x vertical exaggeration

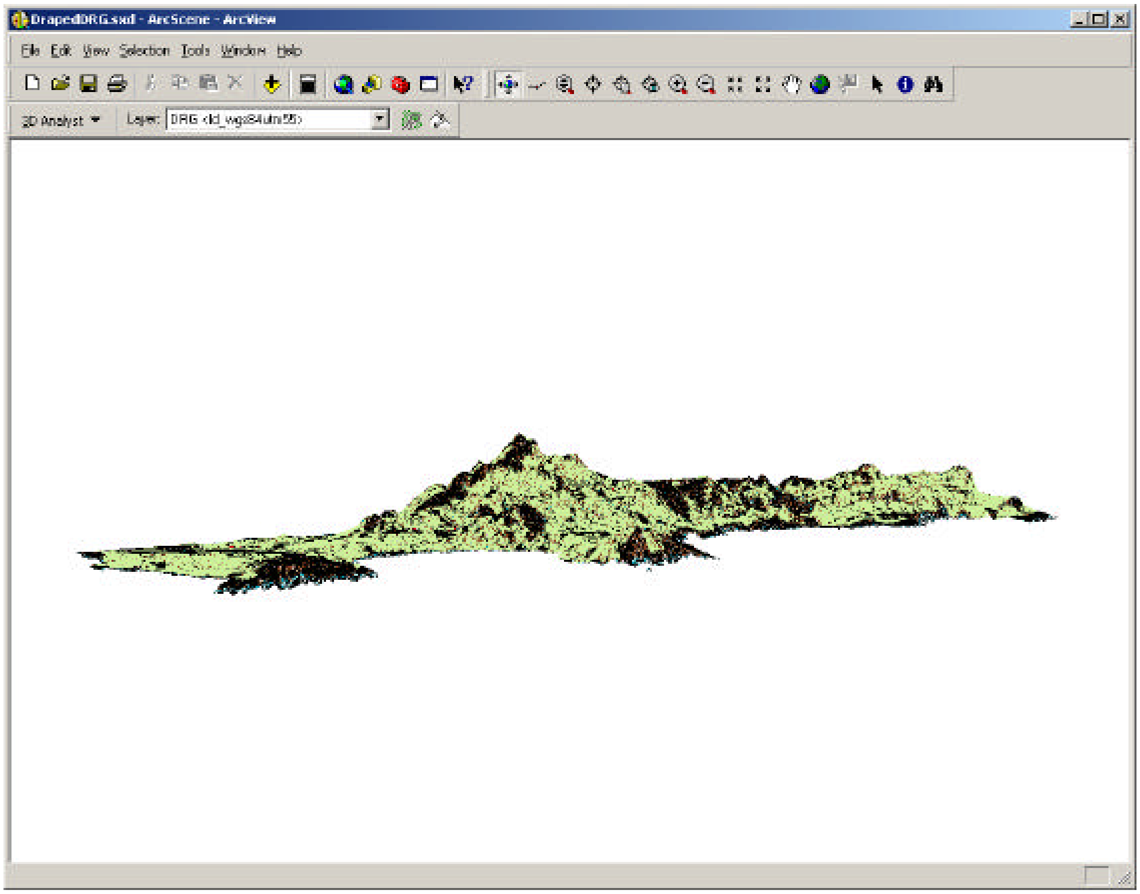


Figure 75: ArcScene of Saipan's DRG draped over the DEM with 5x vertical exaggeration

Publication

Once the data were in the ArcMap documents for the islands, two ArcMap documents of the Mariana Islands were created: one with all of the islands georeferenced to each other (Figure 76), and another with each island in a separate data frame (Figure 77). All of the data layers from the individual island’s GIS were added to both of the overall maps.

Finally, the seven ArcMap documents were published using ArcMap's Publisher toolbar. Publishing maps allows them to be used by ESRI's free ArcReader software. Before the maps were published, the maps were changed to store relative file names rather than the default of absolute file names. Relative file names were used to allow easy movement of the maps from one physical devise to another without having to modify the source document and republishing.

The working and published maps, with the associated data, are available in digital format. See the conclusions for contact information.

Figure 76: Spatially correct map of the Mariana Islands

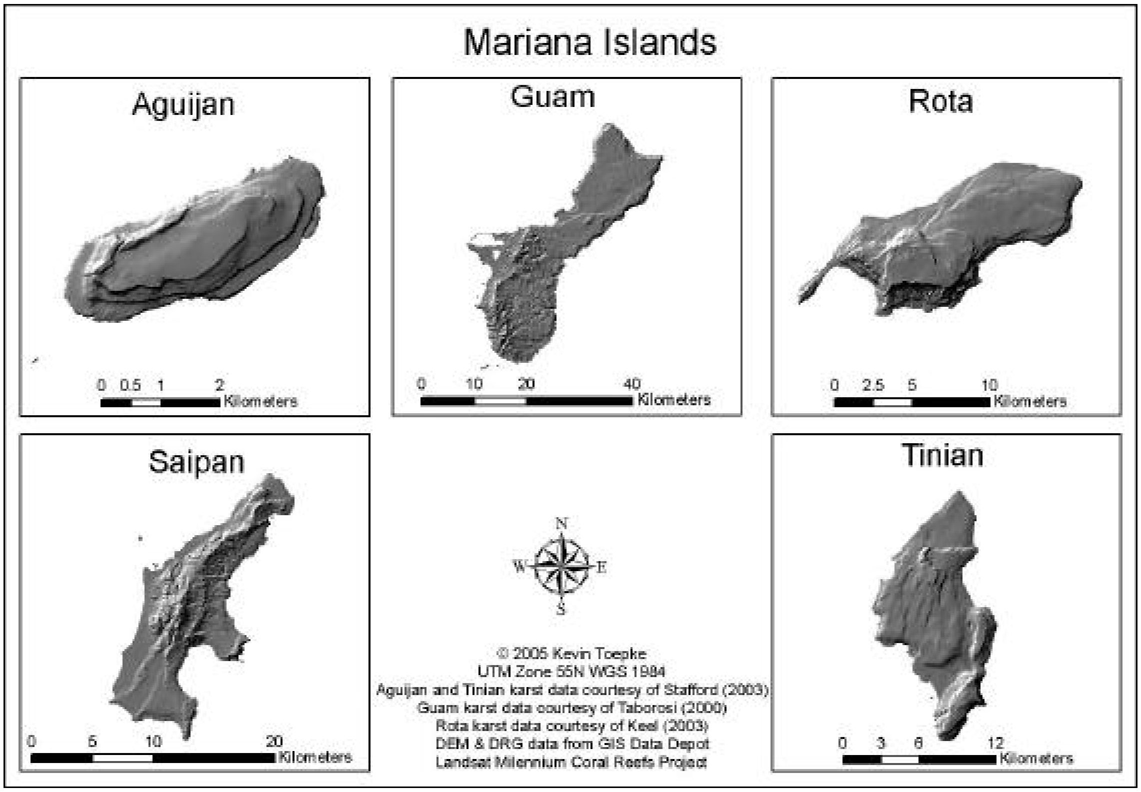
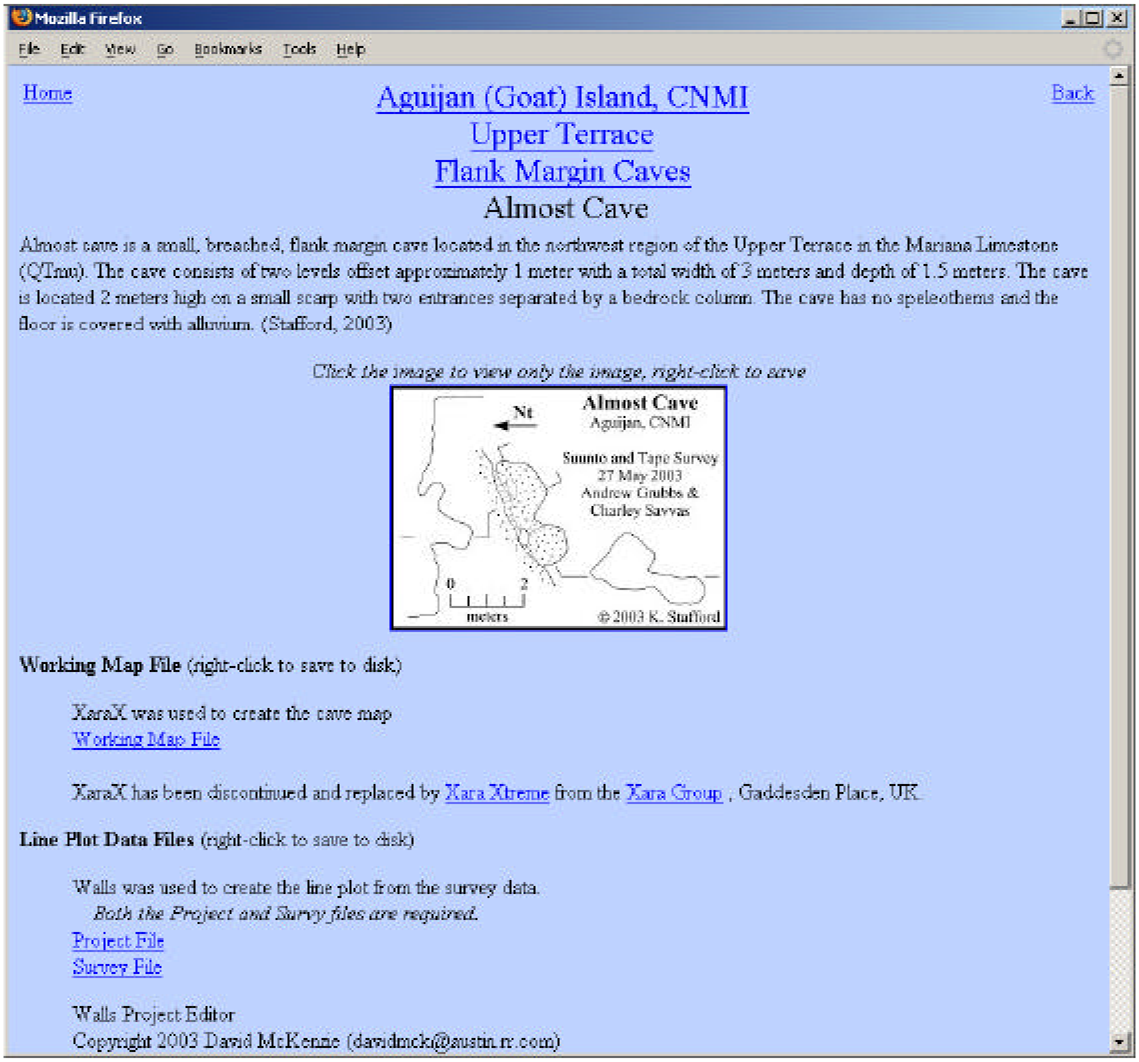


Figure 77: Map of the Mariana Islands with each island in a separate data frame

HTML (Web Page) Navigation

Once the descriptive GIS's for the islands were complete, additional work was done on the HTML pages to improve the "look and feel", navigation, and increase the information content. Each page was given a title, "back" and "home" navigation links, and links to the parent, grandparent, and great-grandparent pages, as appropriate. The "back" link returns the user to the previous navigation page and the "home" link sends the user to the home page for the project, described later. For example, the HTML page for Almost Cave (Figure 78), a flank margin cave on the Upper Terrace of Aguijan, has links to its parent (Flank Margin Caves on the Upper Terrace of Aguijan), grandparent (cave types in the Upper Terrace of Aguijan), and great-grandparent (Aguijan Island, CNMI). Figure 79 and Figure 80 are example pages for a cave type within province (Figure 79), and for a physiographic province (Figure 80). The background color of each page was set to a hexadecimal value of "#BED2FF" to give an impression of smooth, shallow water in the background. Except for the home page for each island, simple text links are used for navigation. Clickable maps were developed for island's home page, and the home page for the project.

The HTML pages are available in digital format. See the conclusions for contact information.



Mozilla Firefox

File Edit View Go Bookmarks Tools Help

Home

Aguijan (Goat) Island, CNMI

Upper Terrace

Flank Margin Caves

Almost Cave

Back

Almost cave is a small, breached, flank margin cave located in the northwest region of the Upper Terrace in the Mariana Limestone (QTmu). The cave consists of two levels offset approximately 1 meter with a total width of 3 meters and depth of 1.5 meters. The cave is located 2 meters high on a small scarp with two entrances separated by a bedrock column. The cave has no speleothems and the floor is covered with alluvium. (Stafford, 2003)

Click the image to view only the image, right-click to save

Working Map File (right-click to save to disk)

XaraX was used to create the cave map

Working Map File

XaraX has been discontinued and replaced by Xara Xtreme from the Xara Group , Gaddesden Place, UK.

Line Plot Data Files (right-click to save to disk)

Walls was used to create the line plot from the survey data.

Both the Project and Survy files are required.

Project File

Survey File

Walls Project Editor

Copyright 2003 David McKenzie (davidmck@austin.rr.com)

Figure 78: Sample HTML page for a cave showing enhanced navigation

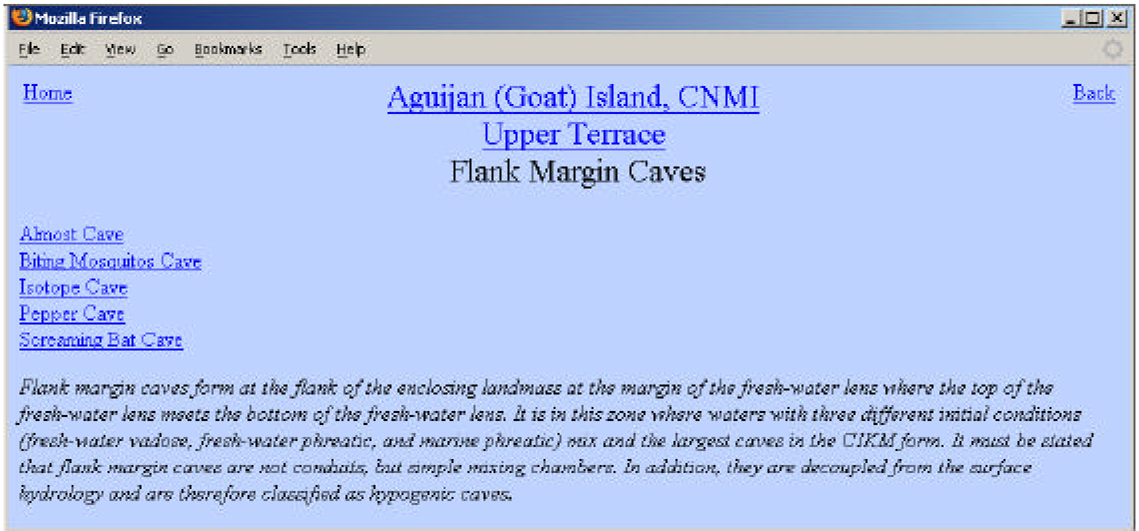


Figure 79: Sample HTML page for a cave type showing enhanced navigation

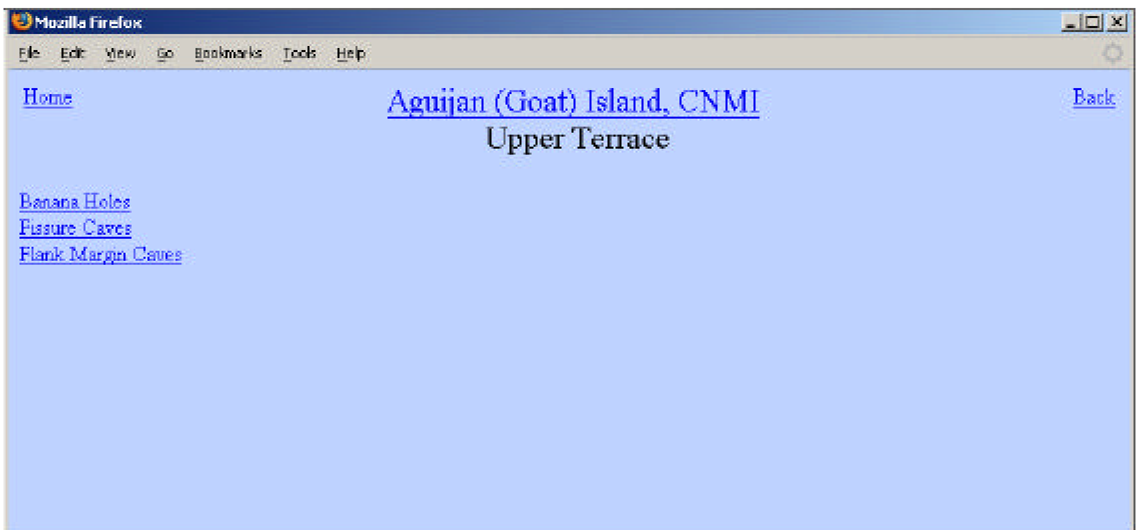


Figure 80: Sample HTML page for a physiographic province showing enhanced navigation

For each island's home page, the following process was followed. First, the hillshade of for the island (Figures 24, 35, 47, 58, and 68) was imported into ArcMap, text was placed on the approximate location of the center of each physiographic province, additional instructional text, a north-arrow, a scale bar, and title were added to the map. The maps background color was set to “Sugilite Sky” (ArcMap’s color name for the hexadecimal "#BED2FF" color value) and the map was exported to a JPEG. This JPEG was imported into a new HTML page in Microsoft FrontPage (Microsoft, 2000c) and clickable rectangles were created around each province’s label. Additionally a drop-down list of provinces was provided as an alternate means of navigation. Finally a link to a HTML page containing an alphabetical listing of caves on the island was added to the bottom of the page. An example of an island’s home page is shown in (Figure 81)

The same process was followed to create a home page for the project except that: the hillshades for all five islands were incorporated into the map, the clickable region was set to an area around the island and the island’s name, the drop-down list contains the island names instead of physiographic provinces, and no link to alphabetical listings were created (Figure 82).

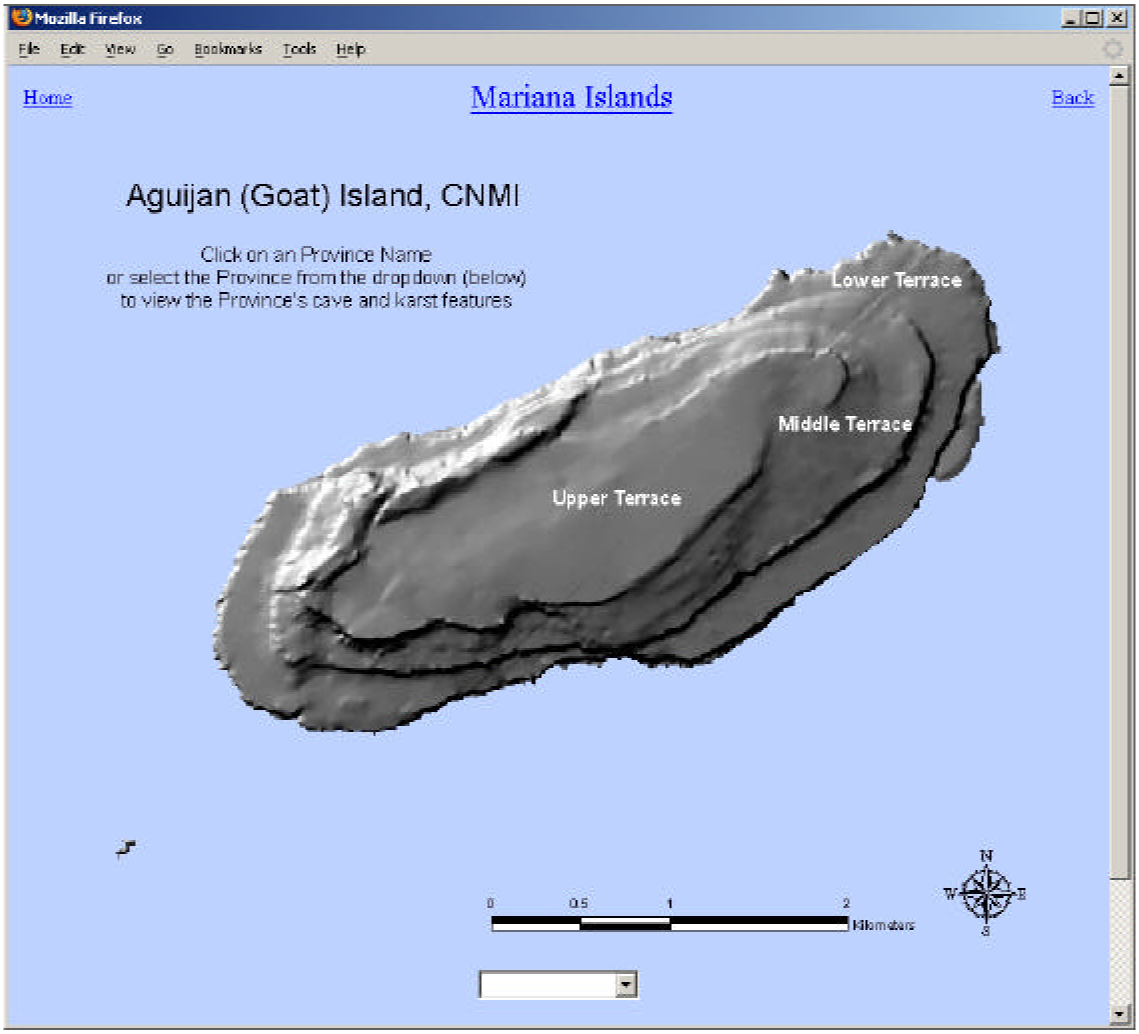


Figure 81: Sample island home page showing enhanced navigation

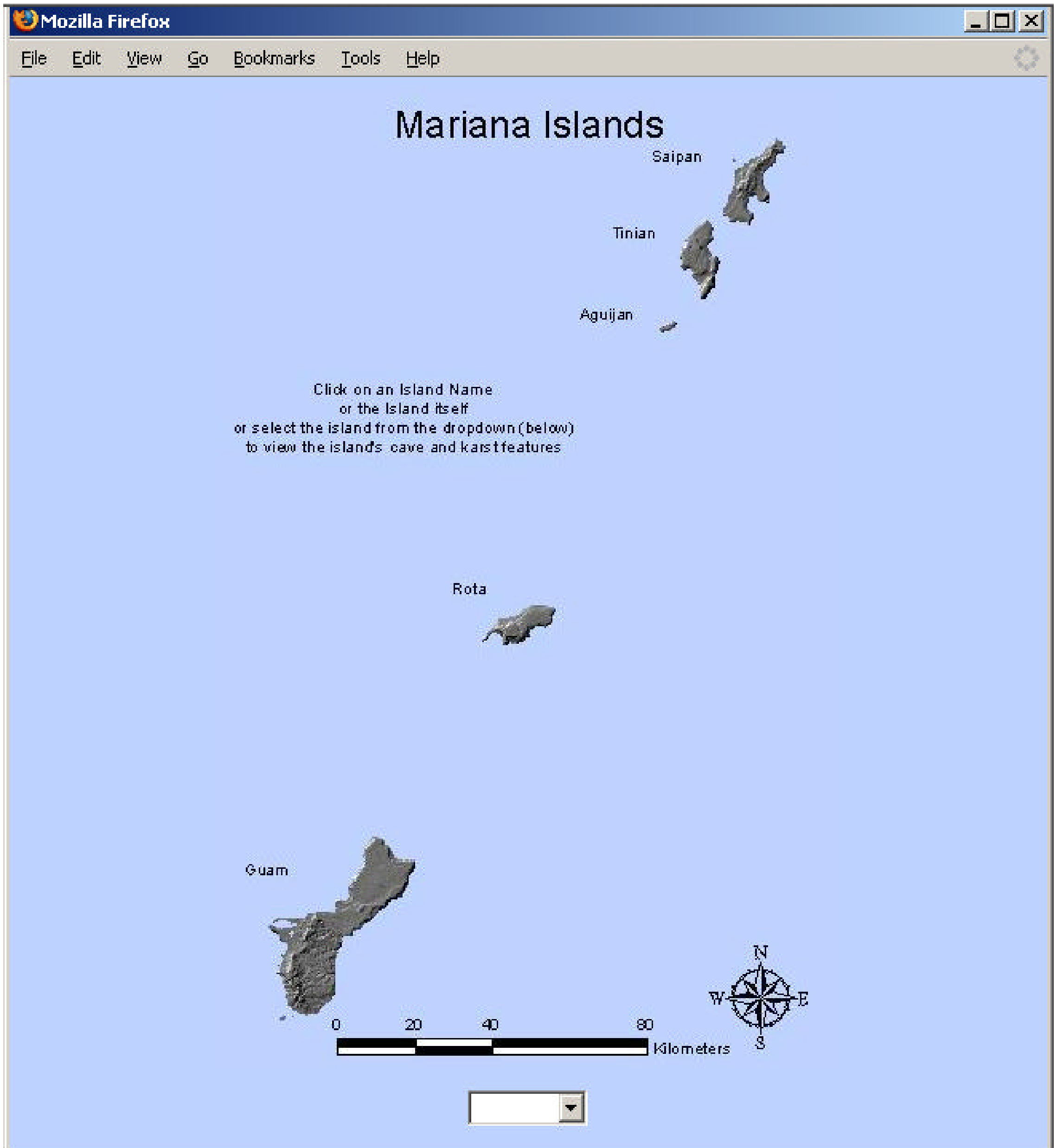


Figure 82: Project homepage showing enhanced layout and navigation

Remote Sensing and GIS Analysis

The first step in the remote sensing part of the project was to remove water, clouds, and cloud shadows from each LANDSAT image. The following processess were followed for each island and are summarized in Figure 83. First, the LANDSAT image with the least cloud cover was chosen for each island. Then water, cloud, and cloud shadow removal was performed. The first step in this process was to perform an unsupervised classification of each image with 255 classes and a target convergence of 0.99. The maximum number of iterations was set high enough to guarantee the target convergence was reached. Each class in this classified image was then manually assigned to either the cloud/cloud shadow/water class or an “other” class. This was done in order to create a mask grid to remove the clouds, cloud shadows, and water from the original LANDSAT scene. A mask grid is used to subset an image, pixel by pixel, in order to remove pixels with undesired reflectance values.

Once the mask grid was created, the mask was applied to the original LANDSAT scene and clouds, cloud shadows, and water were removed. If greater than 90% of the original land surface remained in the masked scene or no additional LANDSAT image of reasonable quality was available, the process was concluded.

However, for Rota, the resulting image had more than 10% of the land surface masked out so additional work was required. An additional LANDSAT scene (NASA, 2005d) was chosen and the clouds, cloud shadows, and water were masked out, as above. This second cloud free image was histogram matched to the first cloud free image and the images were combined. Histogram matching oftn helps standardize radiometry from two different images over the same area. The images were combined by preferentially selecting pixels from the first image that were not clouds, cloud shadows, or water. If the pixel in the first image was cloud, cloud shadow, or water, the matching pixel from the second image was used.

The final step in the cloud, cloud shadow, and water removal process was to recompute the statistics on the images. The cloud free images are show in Figures 84, 85, 86, 87, and 88.

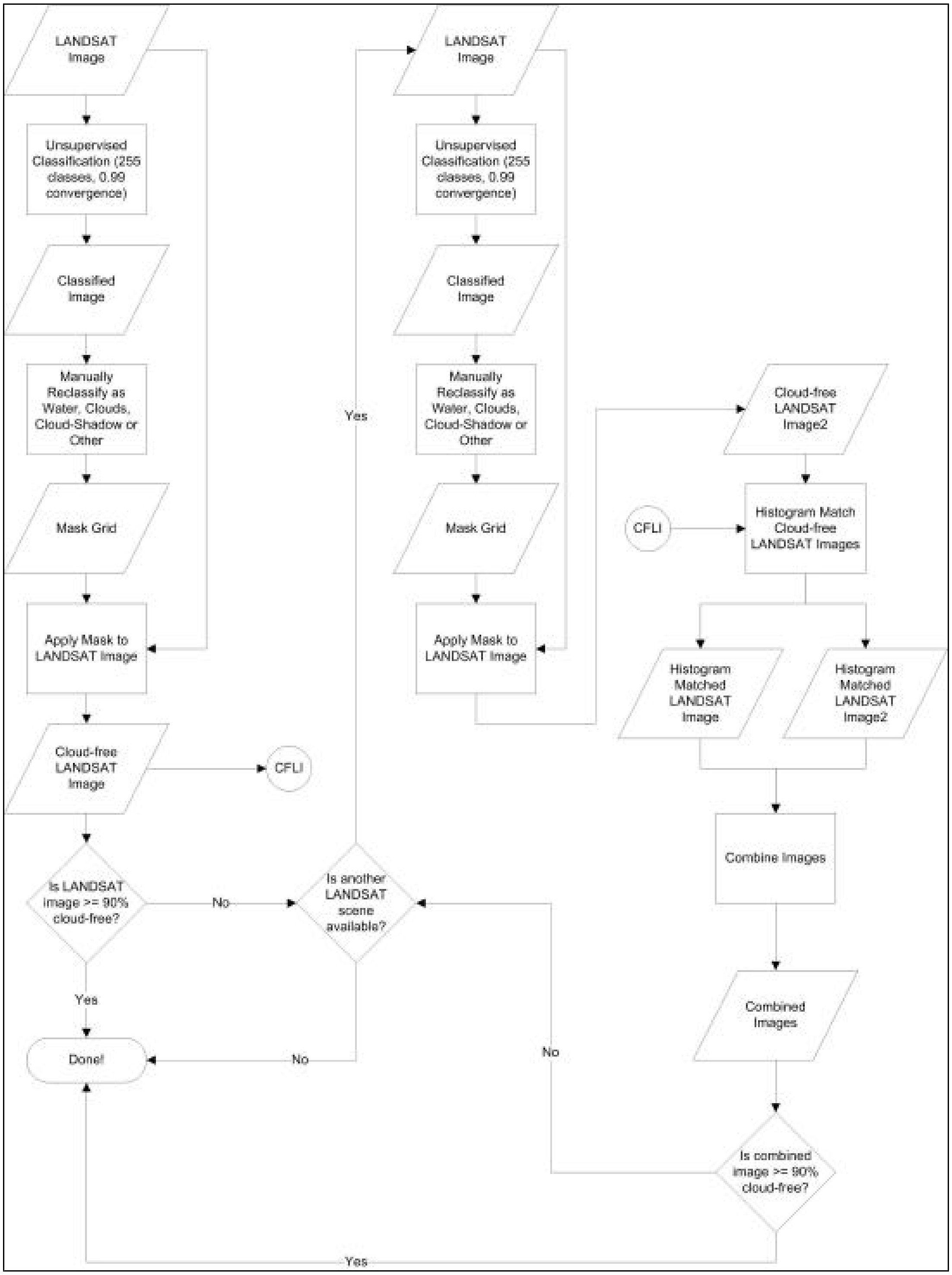


Figure 83: Flowchart of process to remove clouds, cloud shadows and water from LANDSAT images

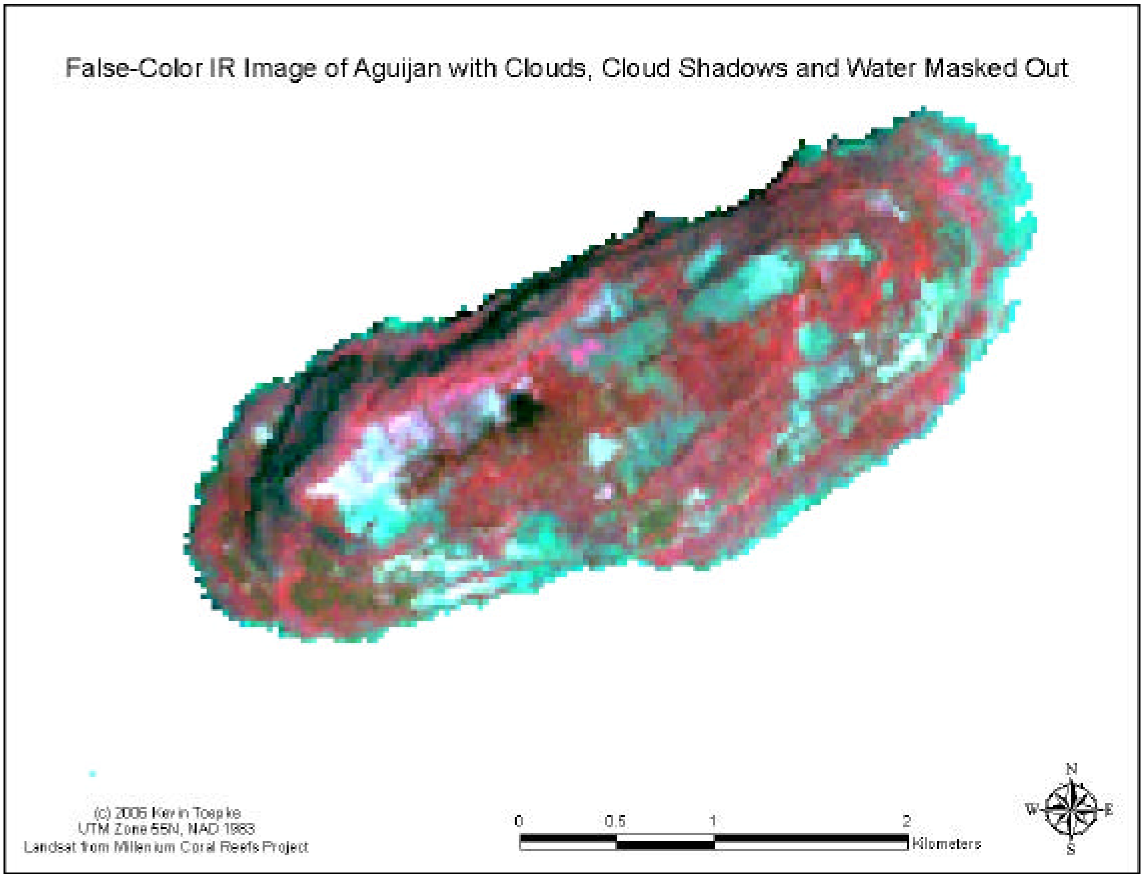


Figure 84: False-color IR LANDSAT image of Aguijan with clouds, cloud shadows, and water masked out

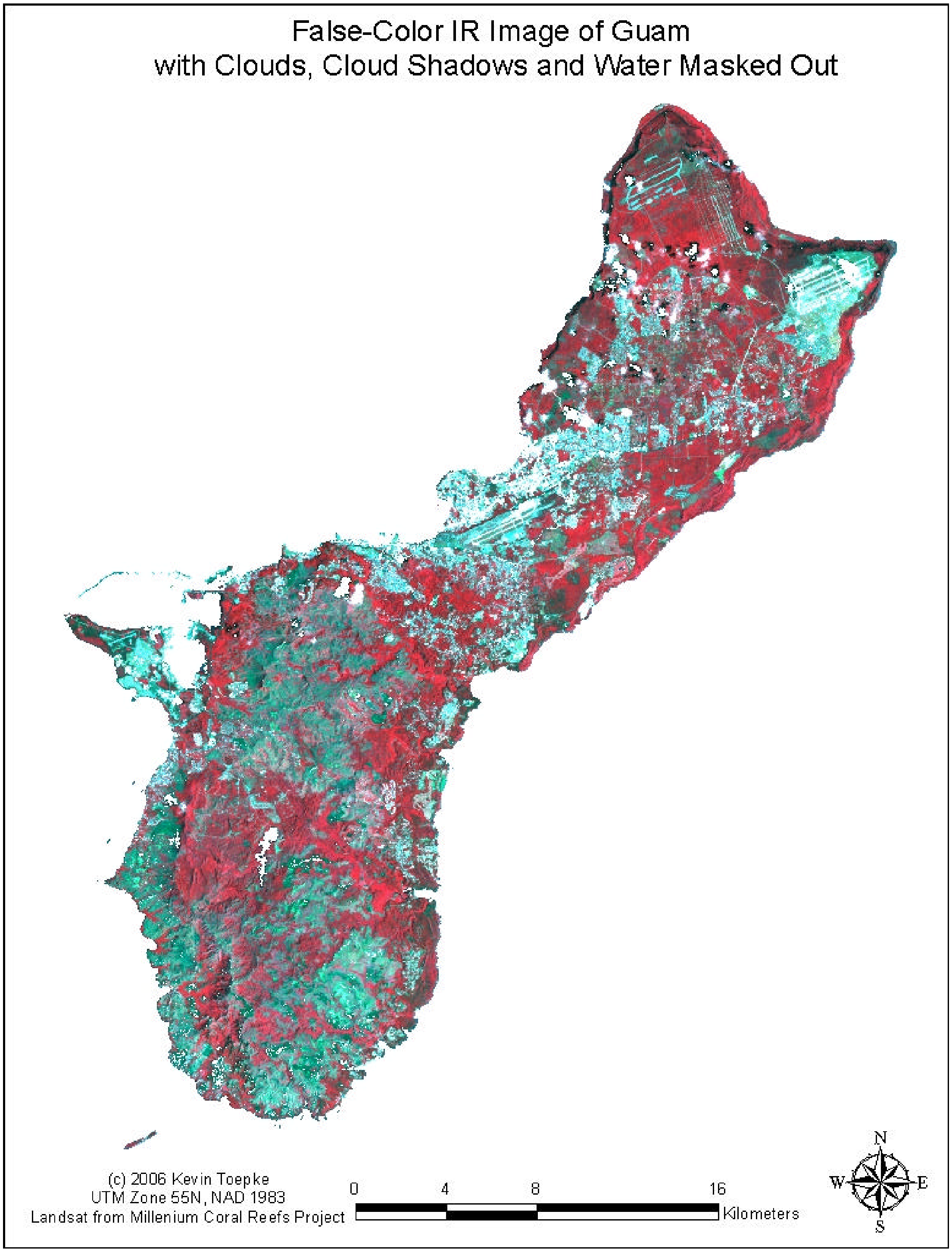


Figure 85: False-color IR LANDSAT image of Guam with clouds, cloud shadows, and water masked out

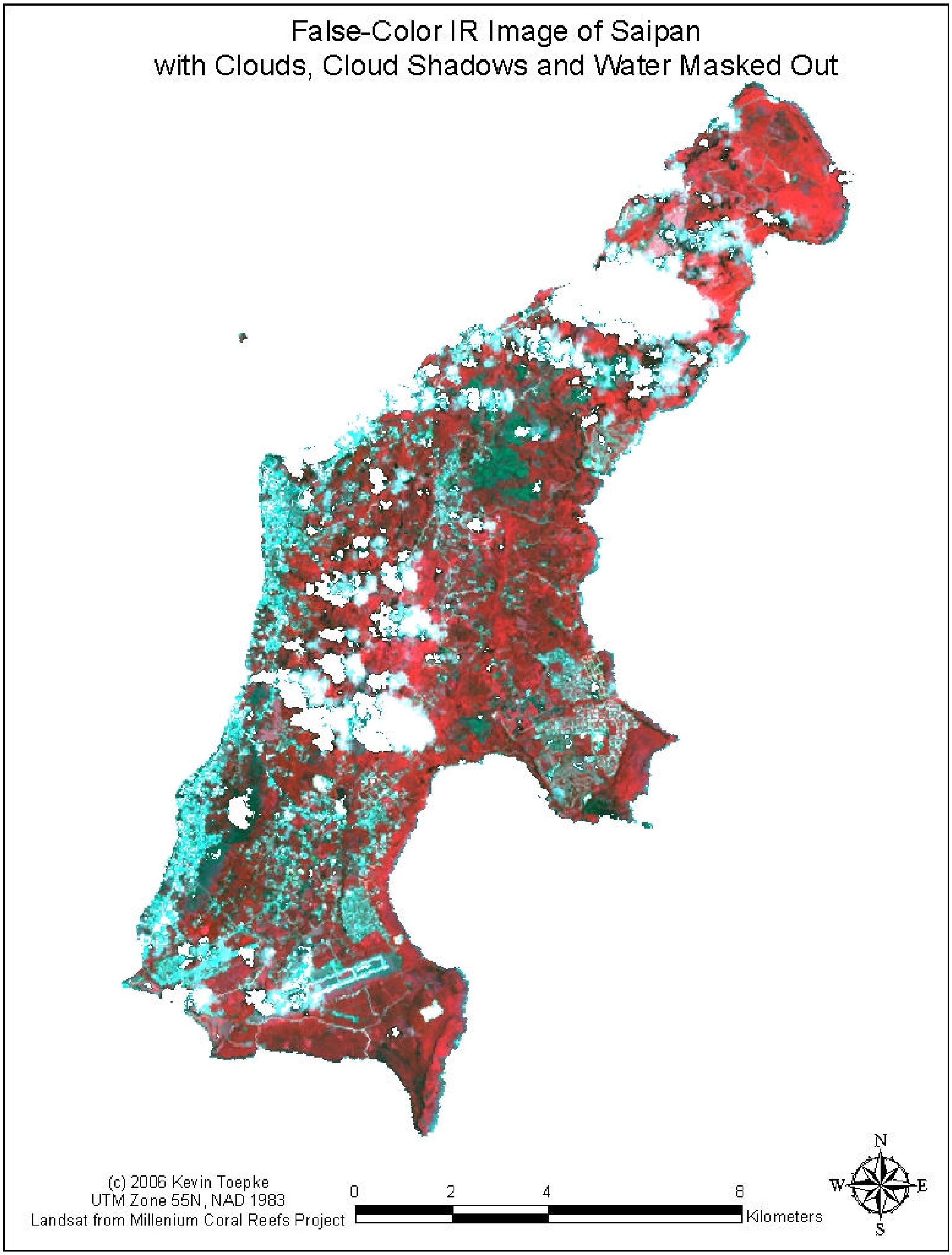


Figure 86: False-color IR LANDSAT image of Saipan with clouds, cloud shadows, and water masked out

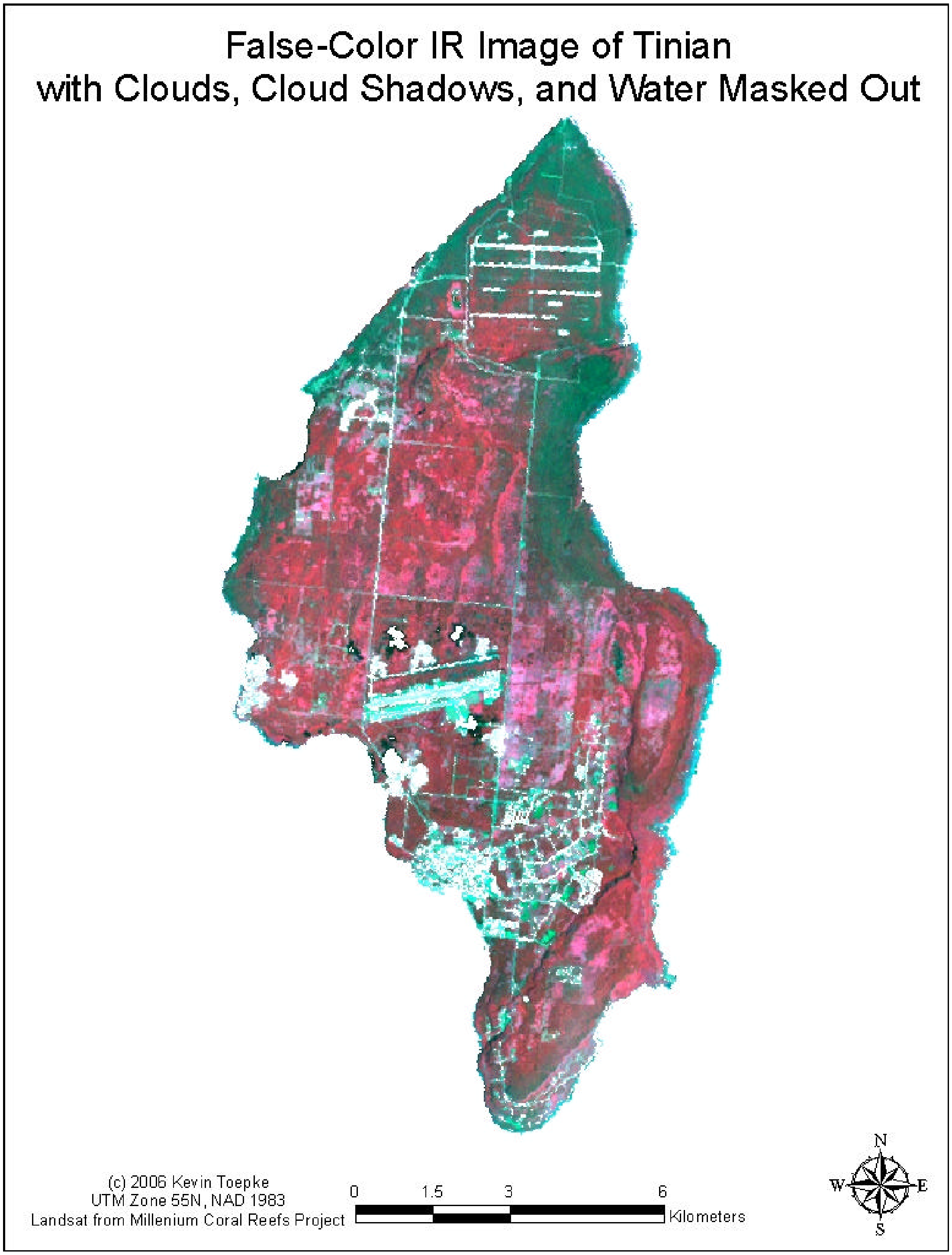


Figure 87: False-color IR LANDSAT image of Tinian with clouds, cloud shadows, and water masked out

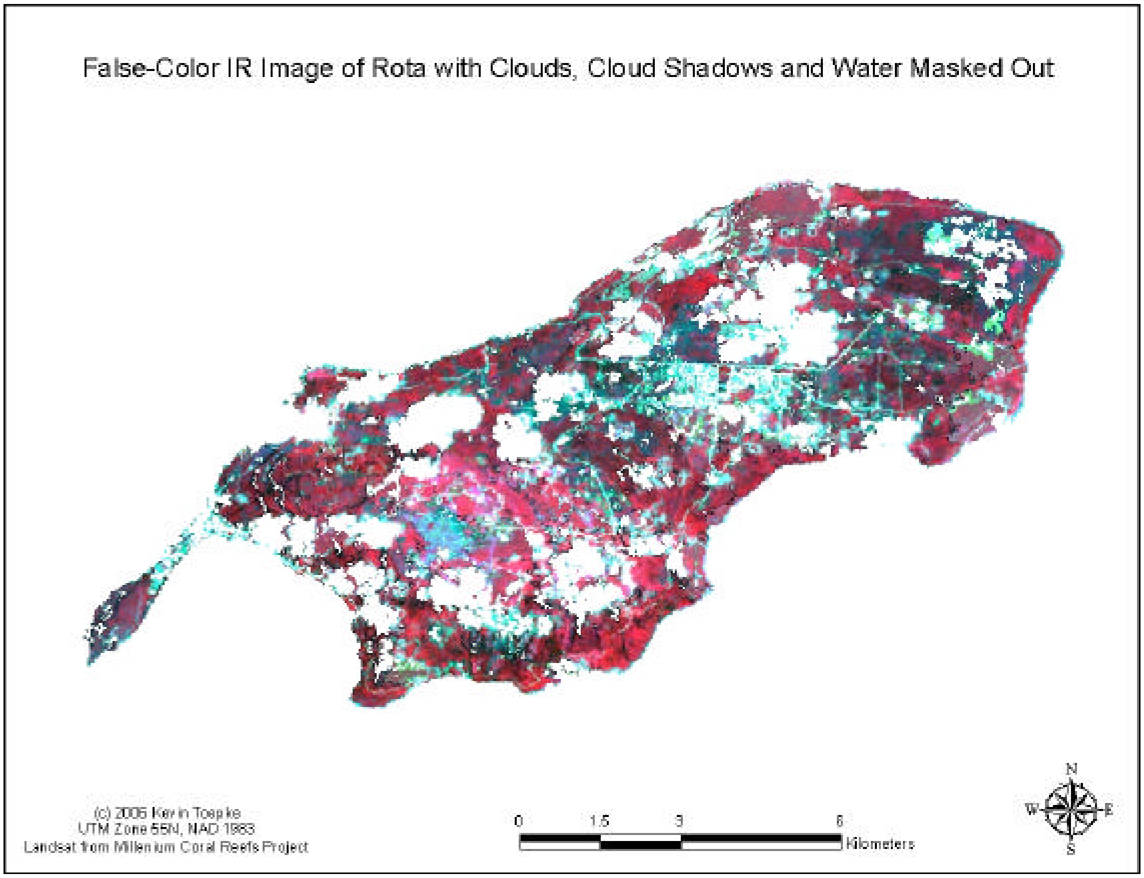


Figure 88: Combined false-color IR LANDSAT image of Rota with clouds, cloud shadows, and water masked out

These masked and combined LANDSAT images were used as input for the NDVI and minerals composite indicies. The minerals composite index is the band ratioing described in Laes et al (unpublished) The NDVI and minerals composite indicies were used as inputs for attempts to classify the exposed bedrock and soils of Guam. The NDVI was used in the attempts to classify the vegetation on Rota (Figure 89).

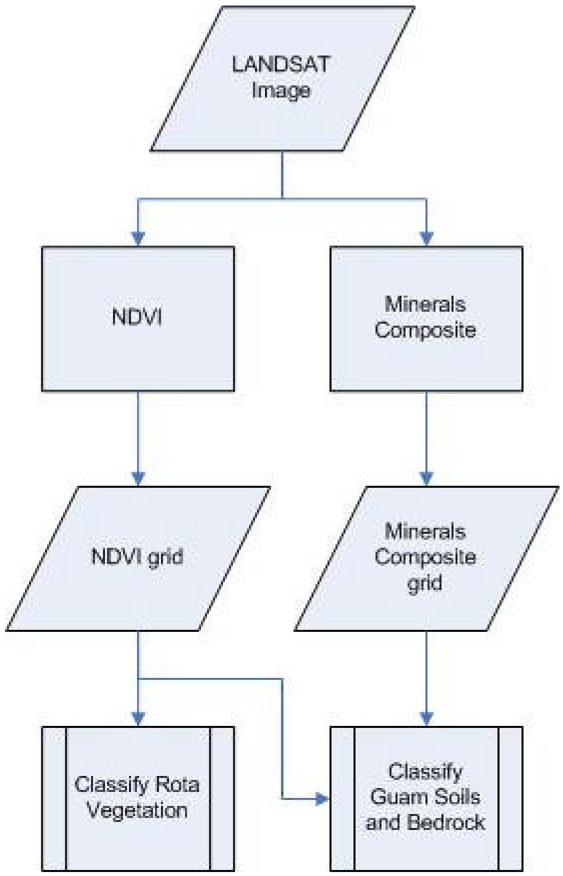


Figure 89: Indicies used in classification attempts

After the NDVI was run against Rota's combined LANDSAT image, the output was analyzed for its ability to identify and classify vegetated pixels as either volcanic vegetation (primarily *Miscanthus*) or limestone vegetation (mixed forests). The results of a supervised classification of the NDVI found that cultivated grass (yards, near roads, etc) has NDVI values identical to *Miscanthus* (Figure 90). A second attempt was made at a supervised classification using the first 7 bands of the LANDSAT images, this attempt also failed because cultivated grass has the same reflectance values as *Miscanthus*. Several other attempts were made to classify Rota's vegetation including:

- Supervised and unsupervised classifications of the cloud free LANDSAT scene of Rota.
- An unsupervised classification with 2048 classes and a convergence of 0.999.
- A supervised classification based on a Tasseled Cap transformation.
- A supervised classification based on Principal Components analysis.

In all cases, it was found that the spectral signature of *Miscanthus* is identical to the spectral signature of the cultivated grasses on the island.

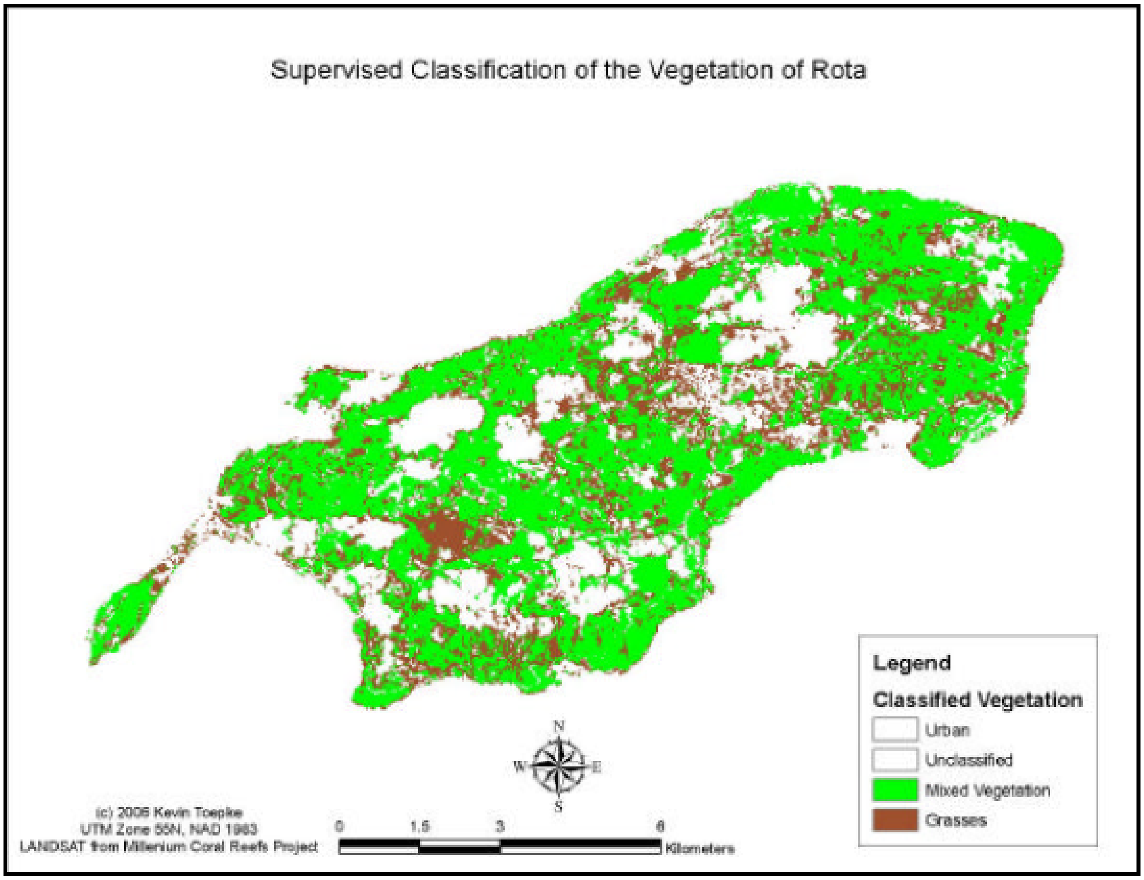


Figure 90: Supervised classification of the vegetation on Rota

After the Guam Minerals Composite was created, the attribute table for each band was copied into a spreadsheet and the histograms of each band were graphed against each other to identify the characteristic cell values for each layer (Figure 90). Significant overlap of the histograms between adjacent bands was observed indicating the potential for considerable class confusion. Many attempts were made to classify the exposed rock and soil as being either volcanic or limestone in origin. Iron rich soils and exposed bedrock were placed in one class, clays, sulfates, and carbonate rich soils were placed in another, and pixels that exhibited significant class confusion (cell values between about 1.4 and 1.7) were placed in a mixed soils class. In each classification attemt, the algorhtim was too aggressive in either placing cells in the mixed soils class or the iron-rich class. When the classification algorithm was too aggressive in placing cells in the mixed-soils class, few, if any, cells were classified as iron-rich. Conversely, when the classification algorithm was too aggressive in placing them in the iron-rich class. This heuristic classification attempt was deemed unsuccessful when visually assesed based on personal fieldwork. Several other attempts were made to classify the exposed rocks and soils using a variety of techniques including supervised and unsupervised classifications. A final supervised classification using 20 training pixels was used to classify the cloud-free Guam LANDSAT image into 5 classifications: mixed vegetation, grasses, exposed carbonates, exposed iron-rich soils and rocks, and water, clouds and urban areas (Figure 92). Because the classifications of urban, clouds, and cloud shadows were not important to the study class confusion across these three classes was accepted. There were not enough contact or soil points to enable the calculation of a reasonable theoretical surface of the limestone/volcanic contact. In addition, this final classification confirmed the fact that cultivated grass and *Miscanthus* have identical spectral signatures.

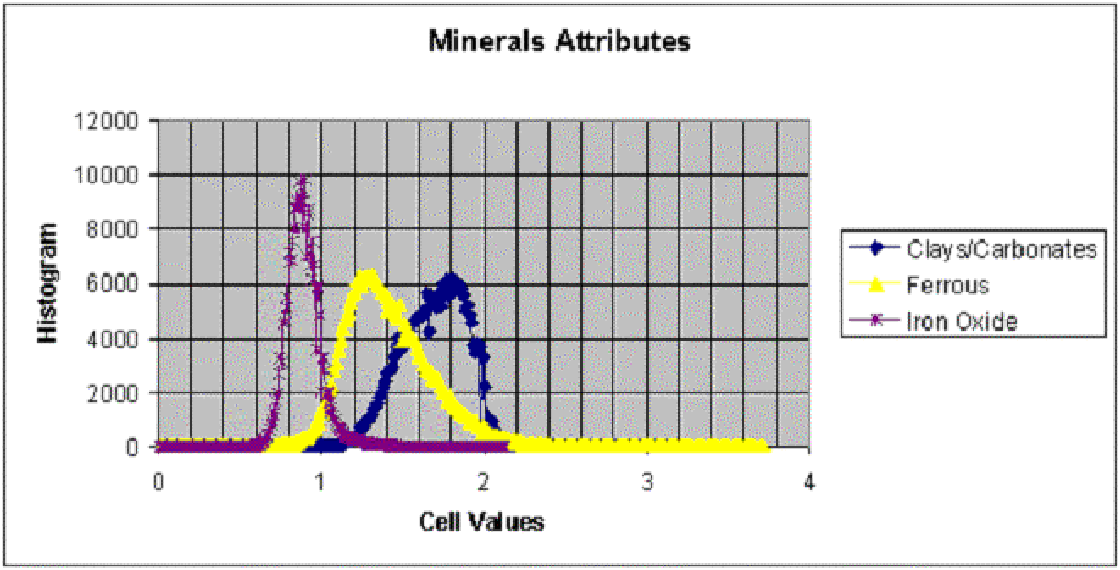


Figure 91: Guam's Masked Minerals Composite image histogram

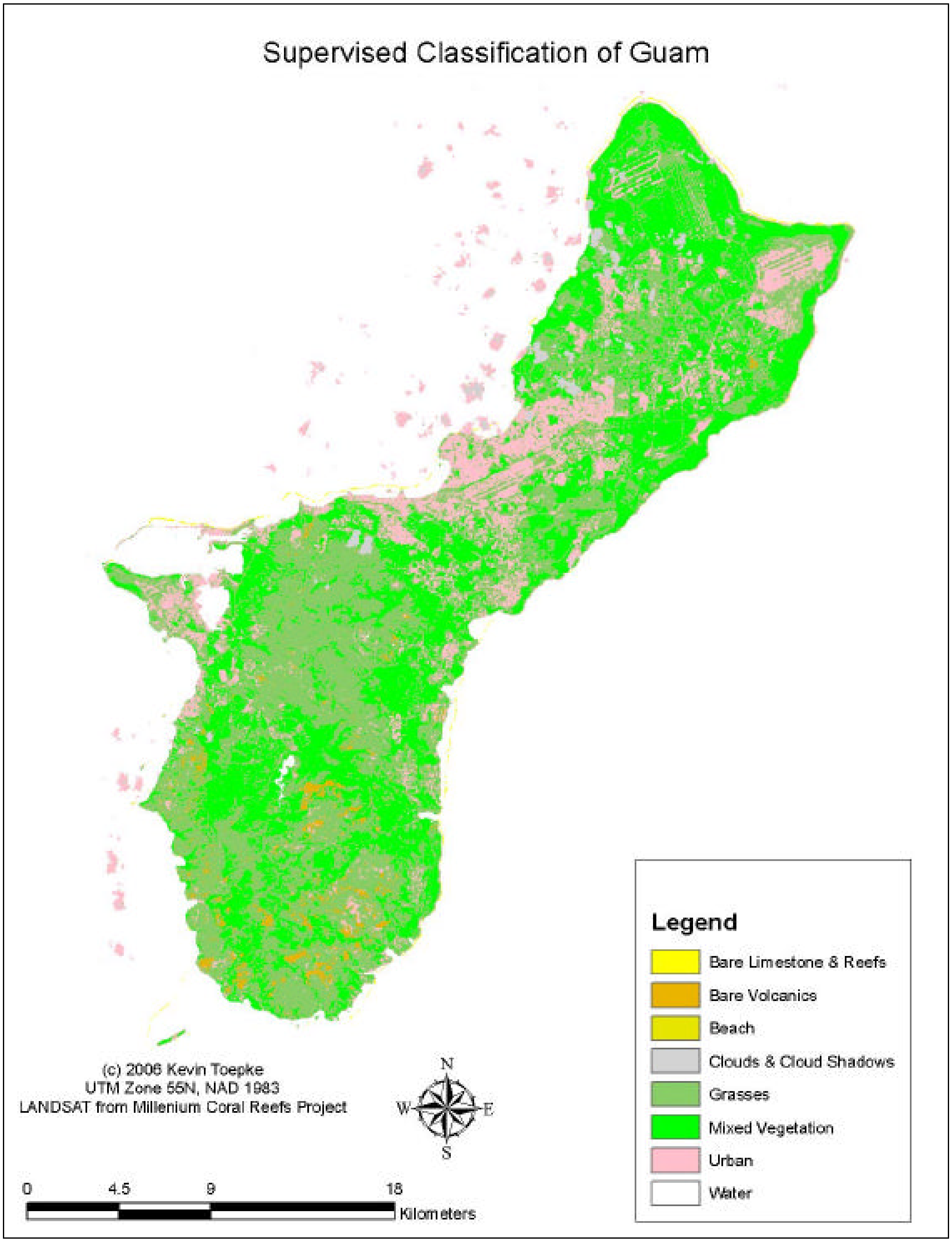


Figure 92: Supervised classification of the vegetation, soils, and exposed bedrock of Guam

CHAPTER VIII

CONCLUSIONS

Descriptive GIS

A good deal of time was spent vetting and organizing the data from the various sources, since each source used a different organization scheme.

One relational geodatabase of cave and karst information, seven maps, ten ArcScene documents, and a series of HTML pages were produced. The geodatabase contains point information for all of the cave and karst features in the Marianas, three sets of contour lines (10-, 25-, and 50m intervals) for each island stored as polylines, and island outlines stored as polygons. The point information of Saipan is incomplete as the data for only four cave features was received. A number of layers from Keel (Table 5 on page 60) and Taborosi (Table 9 on page 102) were also added to the geodatabase as well as maps of Rota and Guam. The seven maps are as follows: Aguijan, Guam, Rota, Saipan, Tinian, and two that cover all five islands. One of which has the islands in the correct spatial arrangement and the other is in more of a poster format, with each island within equally-sized frames. The following information is included in each map:

- Cave and karst features separated by physiographic province and type
- All three sets of contour lines
- The island outline
- DEM
- Hillshade
- DRG
- True-color LANDSAT image
- False-color IR LANDSAT scenes

The cave and karst features, contour lines, and island outlines are retrieved from the database when the map is loaded. The ten ArcScene documents are divided into two per island – one being the DRG draped over the DEM, and the other being the LANDSAT image draped over the DEM. The HTML pages for the cave and karst features contain the feature descriptions, maps, and links to the Walls (McKenzie, 2002) project files and the working map documents (usually in XaraX format (Xara, 1997)). Additional web-publishing quality HTML pages were created to allow normal web navigation from the project's root directory.

The seven maps, ten ArcScene documents, and HTML pages along with the geodatabase provide a good start for organizing the cave and karst data of the Marianas. They provide "one-stop shopping" for information on the caves and karst of the Mariana Islands. This consolidation of information will allow future researchers to identify future project locations and to more effectively target field activities. Additionally, the data from future projects can easily be integrated into the database. However, a good deal of additional work could be performed to enhance the geodatabase and maps such as the addition of additional tables or fields to the geodatabase and the incorporation of these new data into the maps.

Organizing the point, line, and polygon data in a relational geodatabase allows for simplified data management. Future researchers can modify the cave and karst data from a single place. Adding or changing the cave and karst data in the geodatabase immediately propogates the changes in the existing layers used to create the maps.

There were a total of 740 karst features included in the descriptive GIS. Karst features by island are summarized in Table 10, by feature type in Table 11, and by island, province, and feature type in Table 12.

Table 10: Summary of karst features by Island

Island	Number of Features
Aguijan	26
Guam	502
Rota	121
Saipan	3
Tinian	88

Table 11: Summary of karst features by feature type

Feature Type	Number of Features
Abandoned Stream Cave	16
Banana Hole	6
Closed Depression	274
Contact Cave	11
Discharge Feature	67
Fissure Cave	29
Flank Margin Cave	211
Man-made Feature	2
Mixing-zone Fracture Cave	48
Non-Karst	2
Pit Cave	14
Recharge Cave	4
Sea Cave	14
Stream Cave	9
Unknown Origin	33

Table 12: Karst features included in the descriptive GIS summarized by Island, Province, and Feature Type

Island	Province	Feature Type	Number of Features
Aguijan	Lower Terrace	Fissure Cave	2
Aguijan	Lower Terrace	Flank Margin Cave	4
Aguijan	Lower Terrace	Unknown Origin	1
Aguijan	Middle Terrace	Flank Margin Cave	9
Aguijan	Middle Terrace	Mixing-zone Fracture Cave	2
Aguijan	Upper Terrace	Banana Hole	2
Aguijan	Upper Terrace	Fissure Cave	1
Aguijan	Upper Terrace	Flank Margin Cave	5
Guam	Northern Plateau	Abandoned Stream Cave	3
Guam	Northern Plateau	Closed Depression	203
Guam	Northern Plateau	Contact Cave	2
Guam	Northern Plateau	Discharge Feature	59
Guam	Northern Plateau	Flank Margin Cave	56
Guam	Northern Plateau	Mixing-zone Fracture Cave	6
Guam	Northern Plateau	Non-Karst	1
Guam	Northern Plateau	Pit Cave	5
Guam	Northern Plateau	Sea Cave	8
Guam	Northern Plateau	Stream Cave	6
Guam	Northern Plateau	Unknown Origin	16
Guam	Southern Coast	Abandoned Stream Cave	8
Guam	Southern Coast	Banana Hole	1
Guam	Southern Coast	Closed Depression	26
Guam	Southern Coast	Flank Margin Cave	18
Guam	Southern Coast	Pit Cave	3
Guam	Southern Coast	Unknown Origin	8
Guam	Southern Interior Basin	Abandoned Stream Cave	2
Guam	Southern Interior Basin	Closed Depression	36
Guam	Southern Interior Basin	Discharge Feature	2
Guam	Southern Interior Basin	Mixing-zone Fracture Cave	1
Guam	Southern Interior Basin	Pit Cave	2
Guam	Southern Interior Basin	Recharge Cave	2
Guam	Southern Interior Basin	Stream Cave	2
Guam	Southern Interior Basin	Unknown Origin	4
Guam	Southern Mountain Range	Abandoned Stream Cave	3
Guam	Southern Mountain Range	Closed Depression	9
Guam	Southern Mountain Range	Contact Cave	1
Guam	Southern Mountain Range	Flank Margin Cave	3
Guam	Southern Mountain Range	Pit Cave	2
Guam	Southern Mountain Range	Stream Cave	1

Table 12 (Continued)

Guam	Southern Mountain Range	Unknown Origin	3
Rota	Sabana	Contact Cave	8
Rota	Sabana	Fissure Cave	15
Rota	Sabana	Flank Margin Cave	35
Rota	Sabana	Man-made Feature	2
Rota	Sabana	Mixing-zone Fracture Cave	14
Rota	Sabana	Non-Karst	1
Rota	Sabana	Sea Cave	4
Rota	Sabana	Unknown Origin	1
Rota	Sinapolo	Fissure Cave	3
Rota	Sinapolo	Flank Margin Cave	14
Rota	Sinapolo	Mixing-zone Fracture Cave	20
Rota	Sinapolo	Pit Cave	1
Rota	Taipingot	Flank Margin Cave	1
Rota	Taipingot	Mixing-zone Fracture Cave	1
Rota	Taipingot	Sea Cave	1
Saipan	Low Platforms and Terraces	Discharge Feature	1
Saipan	Low Platforms and Terraces	Flank Margin Cave	1
Saipan	Low Platforms and Terraces	Sea Cave	1
Tinian	Central Plateau	Banana Hole	1
Tinian	Central Plateau	Discharge Feature	1
Tinian	Central Plateau	Fissure Cave	2
Tinian	Central Plateau	Flank Margin Cave	22
Tinian	Central Plateau	Recharge Cave	1
Tinian	Median Valley	Banana Hole	1
Tinian	Median Valley	Discharge Feature	2
Tinian	Median Valley	Fissure Cave	1
Tinian	Median Valley	Flank Margin Cave	13
Tinian	Median Valley	Mixing-zone Fracture Cave	2
Tinian	North-Central Highland	Banana Hole	1
Tinian	North-Central Highland	Flank Margin Cave	3
Tinian	North-Central Highland	Recharge Cave	1
Tinian	Northern Lowland	Discharge Feature	1
Tinian	Northern Lowland	Flank Margin Cave	1
Tinian	Northern Lowland	Mixing-zone Fracture Cave	1
Tinian	Southeastern Ridge	Discharge Feature	1
Tinian	Southeastern Ridge	Fissure Cave	5
Tinian	Southeastern Ridge	Flank Margin Cave	26
Tinian	Southeastern Ridge	Mixing-zone Fracture Cave	1
Tinian	Southeastern Ridge	Pit Cave	1

Additions to the descriptive GIS that are beyond the scope of this master's thesis could be incorporated to make the GIS more valuable to future researchers. Additional tables and fields could be added to the geodatabase. Some examples of metadata that could be included are: researcher names, research dates, textual descriptions, feature size information, and ownership information. The data could be migrated from the single-user Microsoft Access database to a multi-user database, such as Oracle, IBM's DB2, or Microsoft's SQL Server. This would allow the raster data, such as LANDSAT images and DEMs, to be stored in the geodatabase and would allow multiple researchers to simultaneously work with the data.

The maps could be published to the Internet using the ArcIMS extension. Publishing the maps on the Internet would allow for easier access to the data as well as promote collaboration between researchers.

Remote Sensing

The remote sensing aspect of this project was undertaken in an attempt to generate a theoretical surface for the limestone/volcanic subsurface contact.

A great deal of effort was spent attempting to use remote sensing techniques to differentiate between plant species growing primarily on volcanic soils and plant species that grow only on limestone soils. Several techniques were attempted on the Guam scenes including the following:

- Supervised and unsupervised classifications of the original LANDSAT scenes.
- Supervised classification of the computed NDVI image

- Supervised classification of the cloud, cloud-shadow, and water free images.
- Supervised classification of at Tasseled Cap transformation
- Supervised classification of the results of a Principal Components analysis.

However, no technique used successfully discriminated between the *Miscanthus* sword grass and the cultivated grasses on the island. Therefore the original goal of using vegetation differences to identify limestone/volcanic contacts could not be achieved.

A number of attempts were made to classify remotely sensed imagry for discrimination between the limestone and volcanic outcrops and exposed limestone and volcanic soils on Guam. The supervised classification used did not reveal enough exposures necessary for calculating a reasonable theoretical surface of the volcanic/bedrock contact.

The acquired LANDSAT data had sufficient spectral resolution to enable differentiation between the mixed forests and the grassy areas. However, resolution was not for differentiating between the native *Miscanthus* sword grass and cultivated grasses. Hyperspectral imagery, such as the 220 spectral bands provided by Hyperion data from NASA's Earth-Observing 1 (EO-1) satellite (NASA, 2005) might allow for better differentiation between vegetation types.

In addition ancillary data, such as elevation and slope, has been used by Ricchetti (2000) to aid in the classification of geologic material when using LANDSAT data. Further research could be performed to determine what, if any, ancillary data can be used to classify the LANDSAT images. In addition to slope and aspect, the visualization provided by draping the LANDSAT images and the DRGs over the DEMs could be another source of ancillary data.

Digital Format

Many of the results of this thesis are not condusive to a paper document. These results include the working and published maps, the ArcScene documents, the relational geodatabase, and the HTML pages. Contact either the author at kmt92@tuningoracle.com or Dr. John Jenson at WERI at jjenson@uog9.uog.edu for information on how to get copies of the digital data referenced in this document.

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APPENDIX A

CAVE AND KARST INVENTORY OF AGUIJAN

MAPS AND DESCRIPTIONS

The following data is used with permission from Stafford (2003). The only changes made were to make minor spelling and grammatical corrections. The data has been reorganized from its original alphabetical order to being organized alphabetically by province and karst feature type. Table 13 shows the caves of Aguijan in alphabetical order, Table 14 shows the caves of Aguijan alphabetically within cave type, and Table 15 shows them alphabetically within the province. For ease of use, all tables include the page number that the cave's map and description starts.

Table 13: The caves of Aguijan alphabetically by cave name

Cave Name	Cave Type	Province	Page Number
Almost Cave	Flank Margin Cave	Upper Terrace	222
Anvil Cave	Fissure Cave	Upper Terrace	221
Biting Mosquitos Cave	Flank Margin Cave	Upper Terrace	223
Booney Bee Sink	Banana Hole	Upper Terrace	218
Cabrito Cave	Flank Margin Cave	Middle Terrace	205
Diamond Cave	Flank Margin Cave	Lower Terrace	196
Dove Cave	Banana Hole	Upper Terrace	219
Goat Cave	Flank Margin Cave	Lower Terrace	197
Goat Fracture Cave	Fissure Cave	Lower Terrace	194
Hollow Column Cave	Flank Margin Cave	Lower Terrace	199
Insect Bat Cave	Mixing-zone Fracture Cave	Middle Terrace	216
Isotope Cave	Flank Margin Cave	Upper Terrace	225
Liyang Atkiya	Unknown Origin	Lower Terrace	213
Liyang Lomuk	Flank Margin Cave	Middle Terrace	206
Lizard Cave	Flank Margin Cave	Middle Terrace	207
Natural Arch Cave	Flank Margin Cave	Middle Terrace	208
Orphan Kids Cave Complex	Fissure Cave	Lower Terrace	195
Pepper Cave	Flank Margin Cave	Upper Terrace	226
Scorpion Cave	Flank Margin Cave	Middle Terrace	209
Screaming Bat Cave	Flank Margin Cave	Upper Terrace	227
Spider Cave	Flank Margin Cave	Middle Terrace	210
Swarming Termites Cave	Flank Margin Cave	Middle Terrace	211
Swiftlet Cave	Flank Margin Cave	Lower Terrace	211
Toppled Column Cave	Mixing-zone Fracture Cave	Middle Terrace	217
Tridactid Cave Complex	Flank Margin Cave	Middle Terrace	213
Waypoint Cave	Flank Margin Cave	Middle Terrace	214

Table 14: The caves of Aguijan alphabetically by cave type

Cave Name	Cave Type	Province	Page Number
Booney Bee Sink	Banana Hole	Upper Terrace	218
Dove Cave	Banana Hole	Upper Terrace	219
Anvil Cave	Fissure Cave	Upper Terrace	221
Goat Fracture Cave	Fissure Cave	Lower Terrace	194
Orphan Kids Cave Complex	Fissure Cave	Lower Terrace	195
Almost Cave	Flank Margin Cave	Upper Terrace	222
Biting Mosquitos Cave	Flank Margin Cave	Upper Terrace	223
Cabrito Cave	Flank Margin Cave	Middle Terrace	205
Diamond Cave	Flank Margin Cave	Lower Terrace	196
Goat Cave	Flank Margin Cave	Lower Terrace	197
Hollow Column Cave	Flank Margin Cave	Lower Terrace	199
Isotope Cave	Flank Margin Cave	Upper Terrace	225
Liyang Lomuk	Flank Margin Cave	Middle Terrace	206
Lizard Cave	Flank Margin Cave	Middle Terrace	207
Natural Arch Cave	Flank Margin Cave	Middle Terrace	208
Pepper Cave	Flank Margin Cave	Upper Terrace	226
Scorpion Cave	Flank Margin Cave	Middle Terrace	209
Screaming Bat Cave	Flank Margin Cave	Upper Terrace	227
Spider Cave	Flank Margin Cave	Middle Terrace	210
Swarming Termites Cave	Flank Margin Cave	Middle Terrace	211
Swiftlet Cave	Flank Margin Cave	Lower Terrace	211
Tridactid Cave Complex	Flank Margin Cave	Middle Terrace	213
Waypoint Cave	Flank Margin Cave	Middle Terrace	214
Insect Bat Cave	Mixing-zone Fracture Cave	Middle Terrace	216
Toppled Column Cave	Mixing-zone Fracture Cave	Middle Terrace	217
Liyang Atkiya	Unknown Origin	Lower Terrace	213

Table 15: The caves of Aguijan alphabetically by province

Cave Name	Cave Type	Province	Page Number
Diamond Cave	Flank Margin Cave	Lower Terrace	196
Goat Cave	Flank Margin Cave	Lower Terrace	197
Goat Fracture Cave	Fissure Cave	Lower Terrace	194
Hollow Column Cave	Flank Margin Cave	Lower Terrace	199
Liyang Atkiya	Unknown Origin	Lower Terrace	213
Orphan Kids Cave Complex	Fissure Cave	Lower Terrace	195
Swiftlet Cave	Flank Margin Cave	Lower Terrace	211
Cabrito Cave	Flank Margin Cave	Middle Terrace	205
Insect Bat Cave	Mixing-zone Fracture Cave	Middle Terrace	216
Liyang Lomuk	Flank Margin Cave	Middle Terrace	206
Lizard Cave	Flank Margin Cave	Middle Terrace	207
Natural Arch Cave	Flank Margin Cave	Middle Terrace	208
Scorpion Cave	Flank Margin Cave	Middle Terrace	209
Spider Cave	Flank Margin Cave	Middle Terrace	210
Swarming Termites Cave	Flank Margin Cave	Middle Terrace	211
Toppled Column Cave	Mixing-zone Fracture Cave	Middle Terrace	217
Tridactid Cave Complex	Flank Margin Cave	Middle Terrace	213
Waypoint Cave	Flank Margin Cave	Middle Terrace	214
Almost Cave	Flank Margin Cave	Upper Terrace	222
Anvil Cave	Fissure Cave	Upper Terrace	221
Biting Mosquitos Cave	Flank Margin Cave	Upper Terrace	223
Booney Bee Sink	Banana Hole	Upper Terrace	218
Dove Cave	Banana Hole	Upper Terrace	219
Isotope Cave	Flank Margin Cave	Upper Terrace	225
Pepper Cave	Flank Margin Cave	Upper Terrace	226
Screaming Bat Cave	Flank Margin Cave	Upper Terrace	227

LOWER TERRACE

Fissure Caves

Goat Fracture Cave

Goat Fracture Cave is a large fracture oriented at 15^o, which has two small, roofed portions. The feature is located in the northwest region of the Lower Terrace in the Mariana Limestone (QTmu). It averages 3 meters wide and generally extends 3 to 5 meters below the land surface with a floor composed primarily of breakdown blocks. Minor speleothem deposits are seen along the walls of the feature indicating that it was partially covered in the past. The feature continues for approximately 100 meters to the coast and for a shorter distance inland, but only the roofed portions were surveyed due to time constraints at the time of exploration. The feature appears to be associated with bank-margin failure, but has been modified by dissolution and collapse.

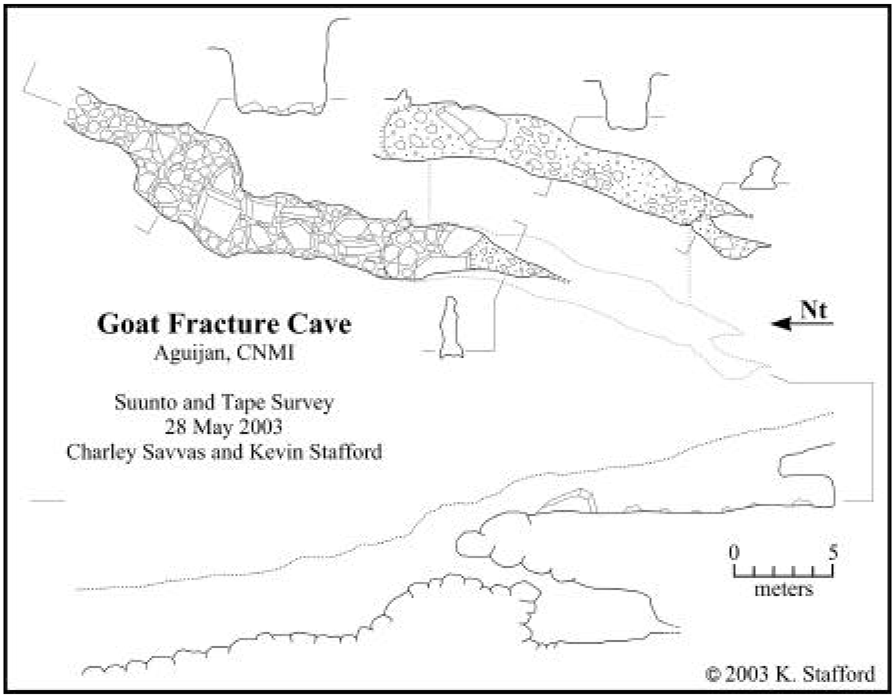

Figure 93: Map of Goat Fracture Cave

Orphan Kids Cave Complex

Orphan Kids Cave Complex is developed in the Mariana Limestone (QTmu) and located on the Lower Terrace on the southern side of Aguijan. This feature consists of three caves spread approximately 75 meters along a low cliff face. The caves are developed along a northwest trending fault with a dips approximately 35^{o} to the northeast. The three caves contain extensive speleothems and breakdown, with the northern feature extending to a depth of 4 meters and the middle and southern feature extend to 17 meters depth. All three features show evidence of extending to greater depths, but collapse and breakdown prevented further exploration. In association with these features, there are numerous dissolutionally enhanced surface fractures, which follow the same general trend. However, no additional features were located that could be entered by humans, nor any that showed signs of speleothems.

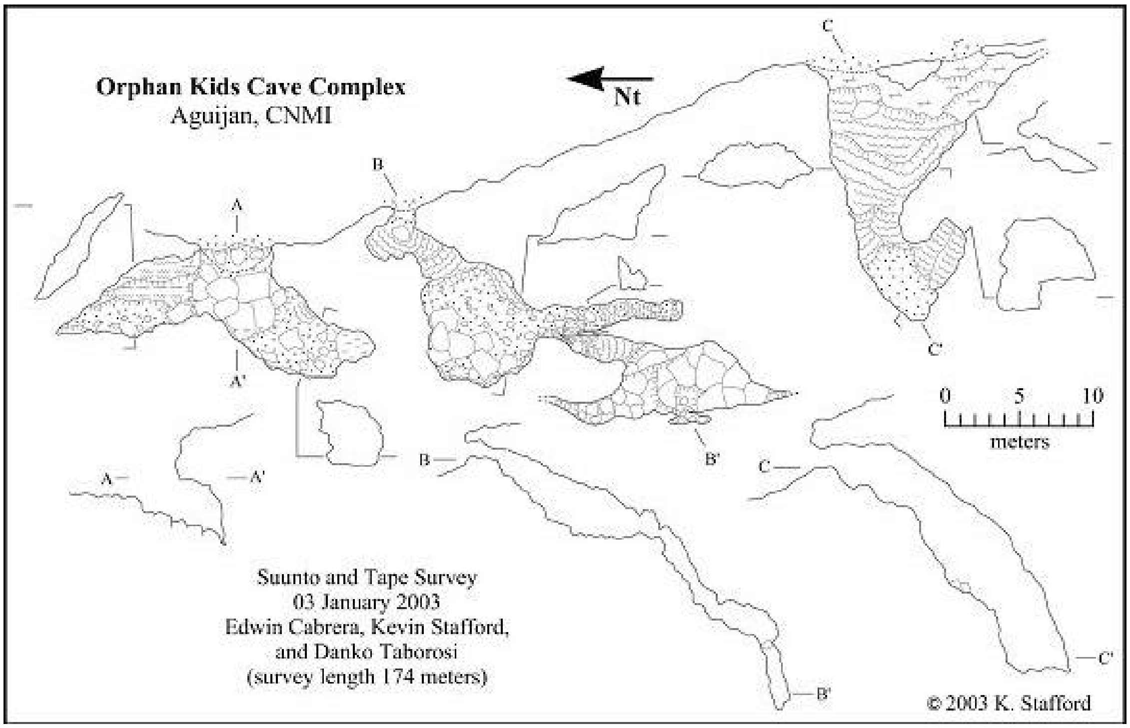

Figure 94: Map of Orphan Kids Cave Complex

Flank Margin Caves

Diamond Cave

This flank margin cave remnant is located on the southern side of Aguijan on the lower terrace in Mariana Limestone (QTmu). It extends inland (north) approximately 26 meters as two passages that are connected in the entrance area, where the ceiling height reaches a maximum of 9 meters at the entrance drip line. Extensive speleothems, including large columns, suggest that the cave was closed for period of time and was then breached by retreat of the cliff margin. This feature showed evidence of extensive use by feral goats.

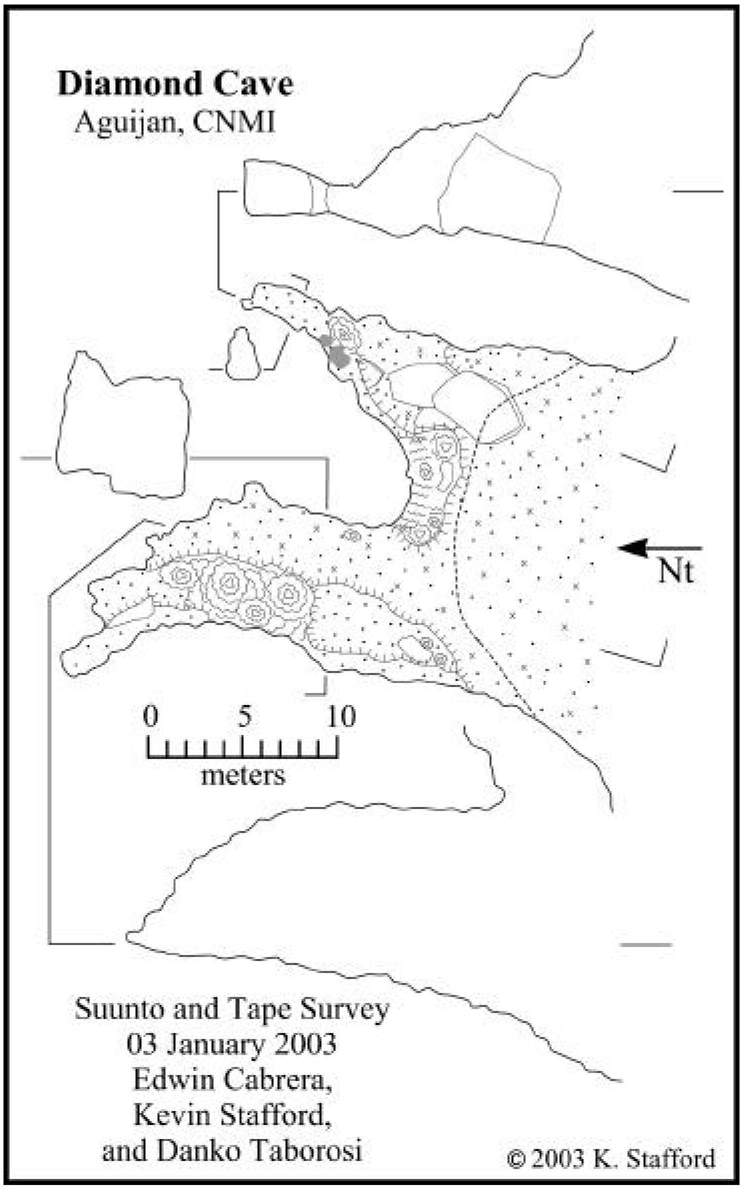

Figure 95: Map of Diamond Cave

Goat Cave

Goat Cave is developed in the Tagpochau Limestone (Tt) and represents a remnant of a large flank margin cave that has been intersected by cliff retreat along the southern cliff that separates the Lower Terrace and Middle Terrace of Aguijan. The feature is semicircular, with a width of 33 meters at the entrance and extending inland (north) for 16 meters with a ceiling height of approximately 14 meters. Just east of the center of the cave is an elevated bedrock area mantled by speleothems including several large stalagmites 3 meters tall. Minor roof collapse has occurred throughout the cave, but it primarily retains its dissolutional morphology. Throughout the cave extensive evidence of occupation by feral goats is found on the thin alluvium layer that covers the majority of the floor.

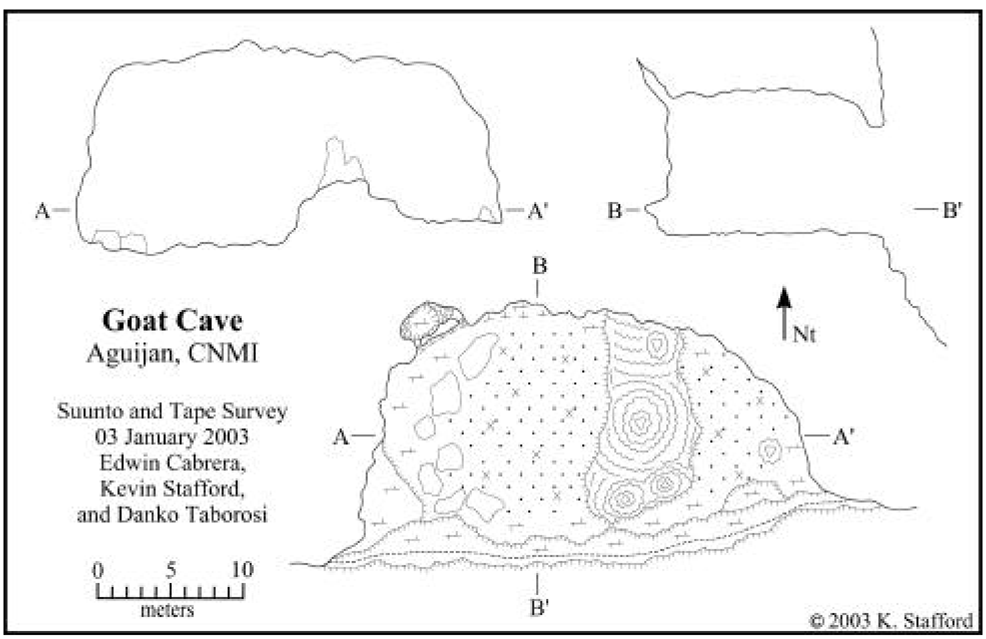

Figure 96: Map of Goat Cave

Hollow Column Cave

Hollow Column Cave is a remnant flank margin cave that has been intersected by cliff retreat on the southern side of Aguijan. It is developed in the Mariana Limestone (QTmu) and extends inland for 20 meters with an average width of 8 meters. In the inland portions of the cave some speleothems are present, including one column that is approximately 3 meters tall. The cave appears to be the side chamber of a larger flank margin cave that has been removed by cliff retreat. A narrow, dissolutionally widened joint trending approximately north is present in the ceiling and may represent structural control on the original dissolution of this chamber.

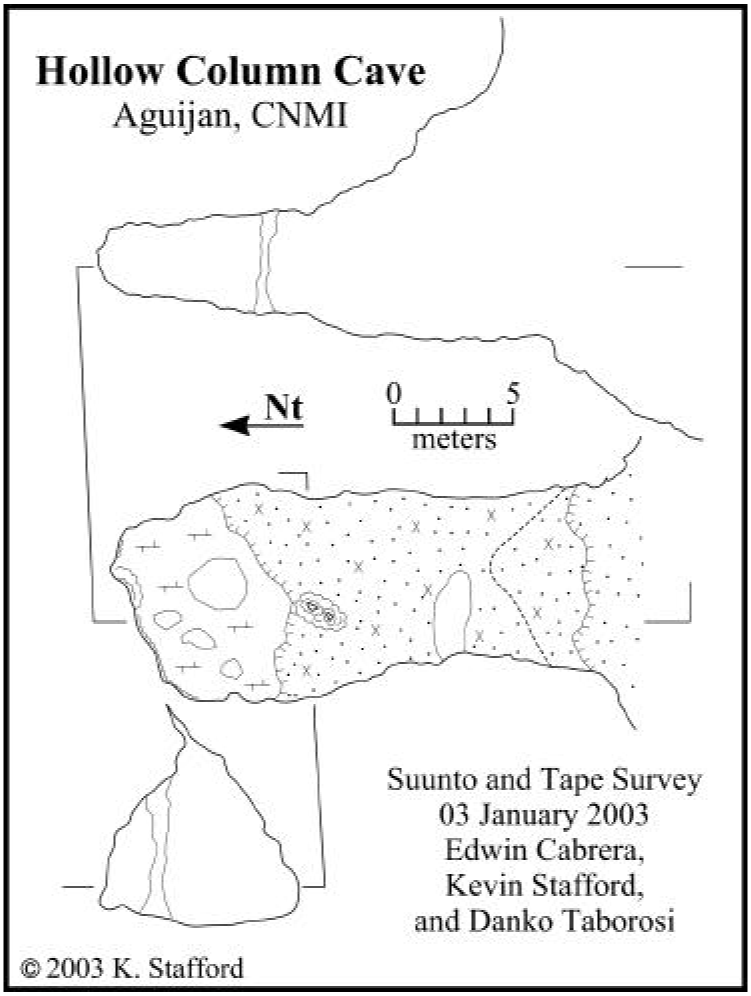

Figure 97: Map of Hollow Column Cave

Swiftlet Cave

Swiftlet Cave is a large, breached flank margin cave on the northwest side of the Lower Terrace approximately 15 meters above sea level. It is developed in the Mariana Limestone (QTmu) and consists of a large chamber 70 meters wide and 30 meters deep that is approximately 18 meters tall in the roofed inland half of the main chamber. The ceiling of the main chamber contains extensive spelean and phototropic speleothems, while the floor is composed of alluvium and large breakdown blocks with elevated bedrock levels on the seaward (northern) side. In the western part of the cave, a passage 8 meters wide and 6 meters tall extends for 20 meters and contains extensive speleothem deposits in the inland portions. In the eastern portion of the cave a steeply dipping, fissure-like passage extends for approximately 50 meters with extensive speleothem deposits throughout and a large colony of Mariana Swiftlets occupying the elevated areas. This eastern extension connects to the main chamber through three small passages, which are reached by short climbs.

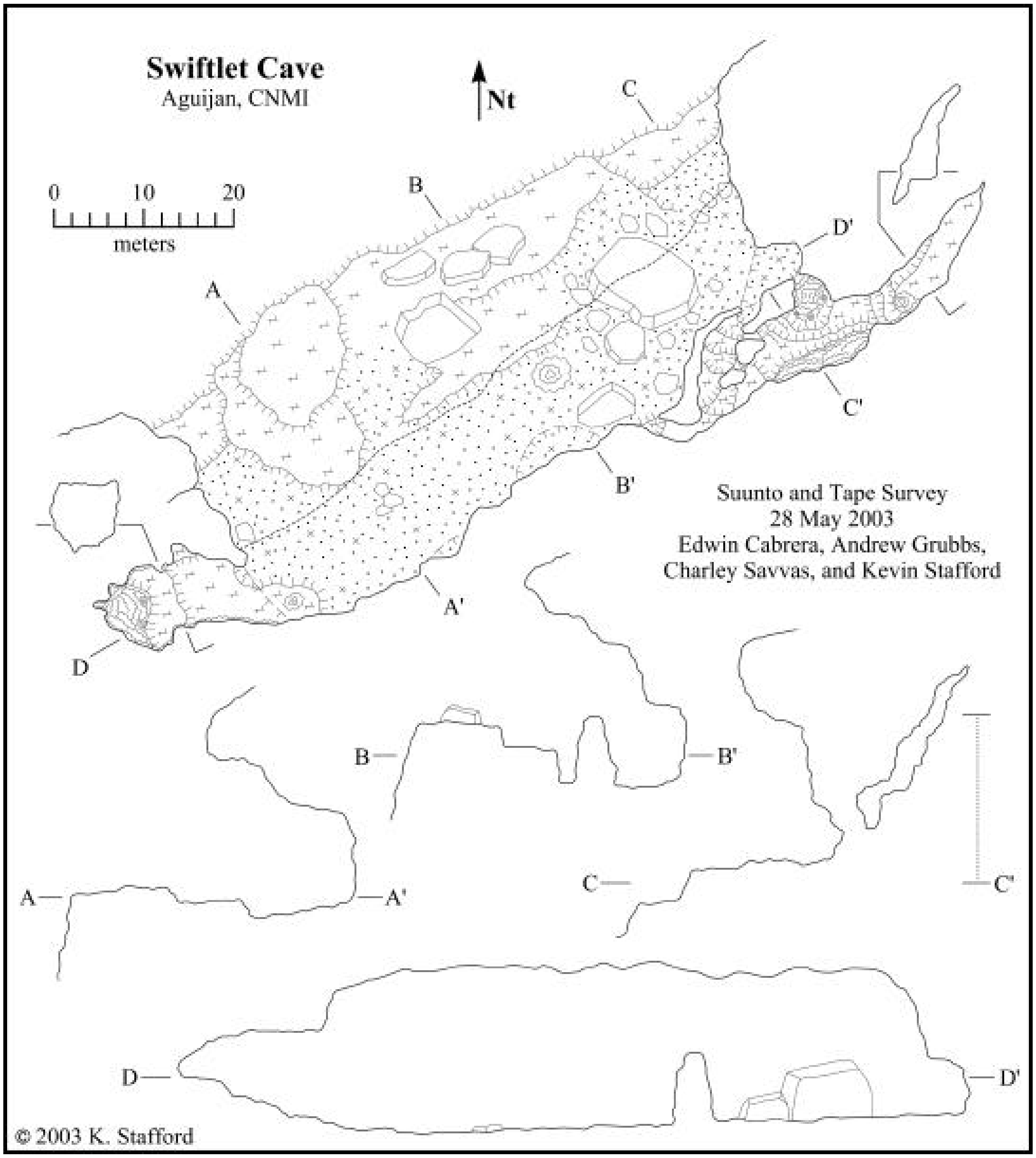

Figure 98: Map of Swiftlet Cave

Caves of Unknown Origin

Liyang Atkiya

Liyang Atkiya is the largest cave yet discovered on Tinian or Aguijan, has a length of 200 meters and a width ranging from 25 meters in the 15-meter tall entrance chamber to 8 meters wide and 5 meters tall in the inland portions. The feature is developed in the Mariana Limestone (QTmu) along the southern side of the Lower Terrace on Aguijan. The entrance is developed along the base of a small cliff and measures approximately 7 meters wide and 1.5 meters tall. From the entrance the cave extends to the north into a large chamber with numerous large breakdown blocks, which form a steep slope over a distance of approximately 80 meters. At the base of the breakdown slope, in the main chamber, are several pools of freshwater and numerous speleothems. This region is also coated with a thin layer of black sediment, possible manganese, which not only coats the walls, but forms thick, black mud and causes a black coloration to the pools of water.

Continuing north, past a man-made rock wall, there is a small 1-meter diameter tube that extends for less than 2 meters into a small chamber containing more black sediment and speleothems. From this small chamber a long, linear passage extends for 75 meters, while continuing to slowly descend deeper. This passage trends northwest and appears to be developed along a fracture. However, large amounts of breakdown from the ceiling completely cover the floor adding complexity to the passage. In the northern portions of the cave, the main passage turns abruptly west and continues in the same fashion, while the original passage trend continues for 30 meters at a slightly higher level and smaller size. The west trending passage was surveyed for 50 meters at a near-level elevation, but two passages continue from this west passage that were not surveyed because of field logistics. However, the main trend continues for approximately 30 meters past the end of the survey as a 2-meter wide, 1-meter tall passage, while a second passage branched off to the south into a series of small, maze-like passages.

This cave represents a complex morphology that does not fit traditional models for carbonate island karst. The large entrance chamber is similar to a flank margin cave that has undergone extensive collapse, but has no side chambers as normally observed in flank margin caves. The long, linear passages appear to follow fractures and in several places retain scallops on the walls that indicate phreatic flow. These scallops are oriented towards the entrance, indicating that water would have flowed upwards through the cave towards the entrance, having originated in the most inland portions of the cave. Much of the interior area of the cave contains extensive breakdown, but low mazy areas may indicate the areas where water entering the explored portion of the cave merged into a single conduit

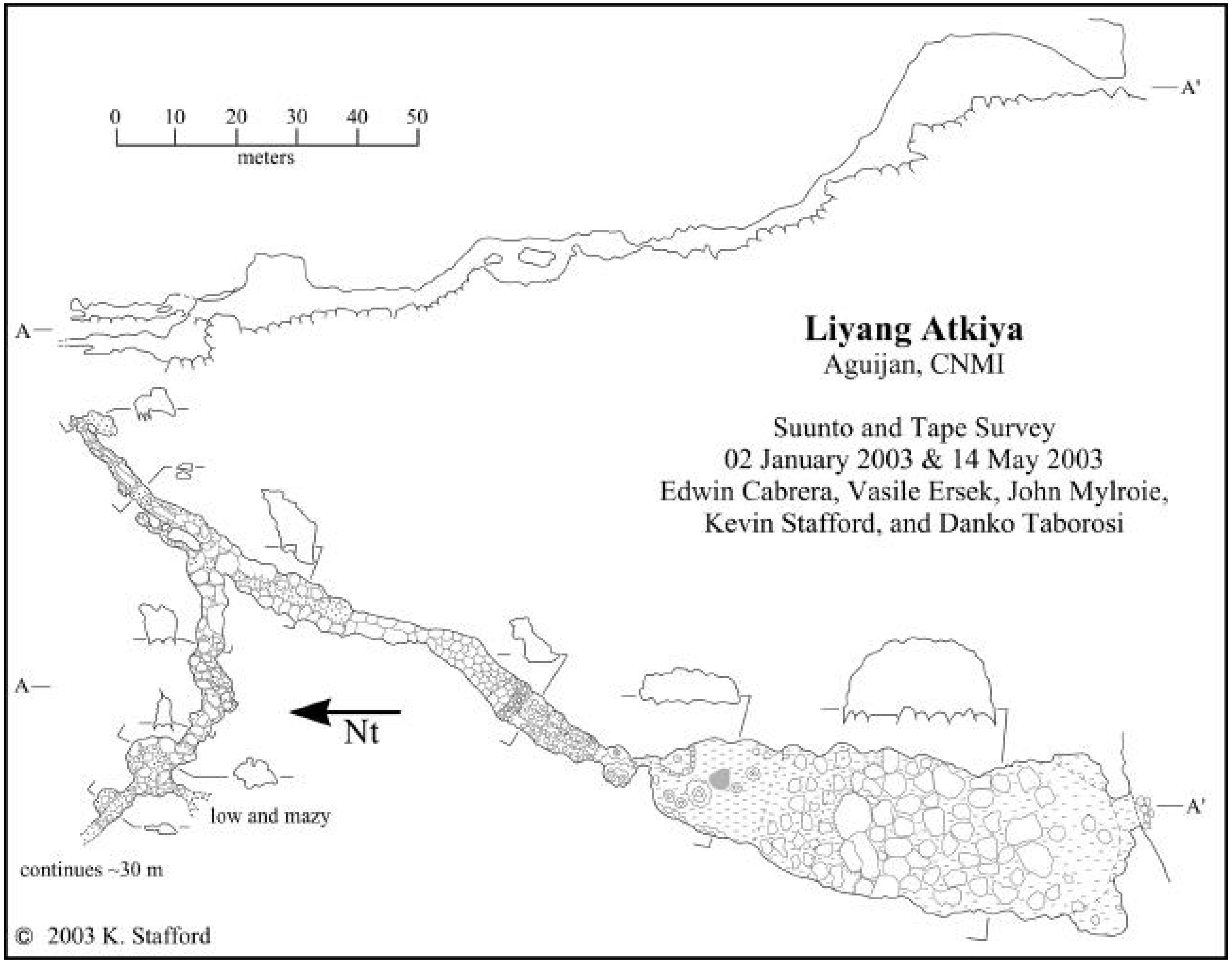

Figure 99: Map of *Liyang Atkiya*.

MIDDLE TERRACE

Flank Margin Caves

Cabrito Cave

Cabrito Cave is a small, breached flank margin cave located in the eastern region of the Middle Terrace in the Mariana Limestone (QTmu). It is 5 meters wide, 2 meters deep and has a maximum height of 2.5 meters. The floor is composed of alluvium in the entrance area and bedrock in the inland portions. The cave contains slightly elevated floor regions in the northern and southern portions, forming a lowered, "trench-like" region in the central portion that is the same elevation as the region near the entrance.

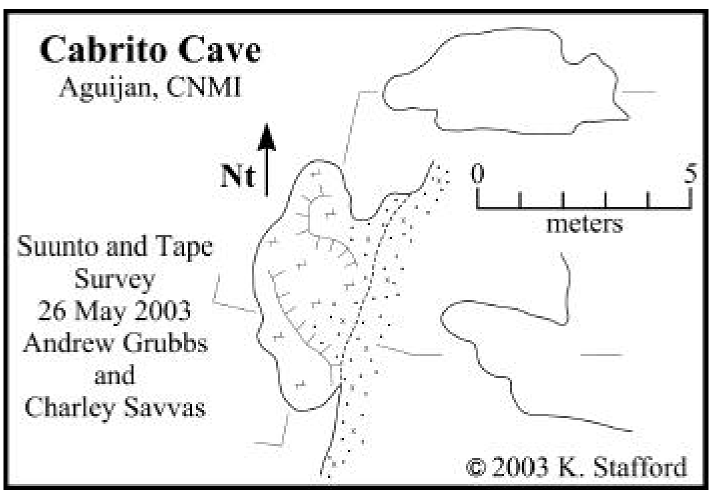

Figure 100: Map of Cabrito Cave

Liyang Lomuk

Liyang Lomuk is a breached, flank margin cave located in the north-central region of the Middle Terrace in the Mariana Limestone (QTmu). It consists of two flank margin cave remnants that extend west of the local scarp. The northern remnant is composed of a main chamber 5 meters wide, 6 meters deep and 3 meters tall, with two small, elevated passages extending from the southwest side of the main chamber. The main floor is composed of alluvium with the elevated areas composed of bedrock. The southern cave remnant is smaller and extends inland 5 meters. It is split vertically by a 0.5 to 1 meter thick bedrock shelf with the lower floor composed of alluvium and a small 0.5-meter deep depression in the east-central part. The cave is named after nearby trees referred to as "*Lomuk*" in the Chamorro language.

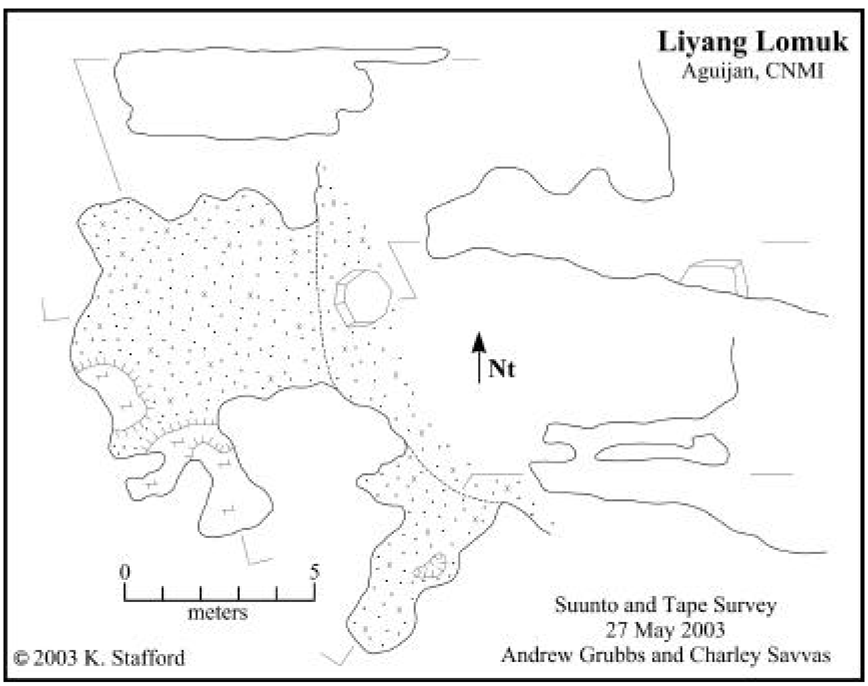

Figure 101: Map of Liyang Lomuk

Lizard Cave

Lizard Cave is a small flank margin cave located on the north-central side of the Middle Terrace in the Mariana Limestone (QTmu). The cave extends inland 7 meters as two passages that average 3 meters wide and less the 2 meters tall. The floor is composed of alluvium and breakdown. One small passage continues from the inland portion of the southwest passage. The entrance area and northwest passage show evidence of extensive use by local fauna, primarily feral goats.

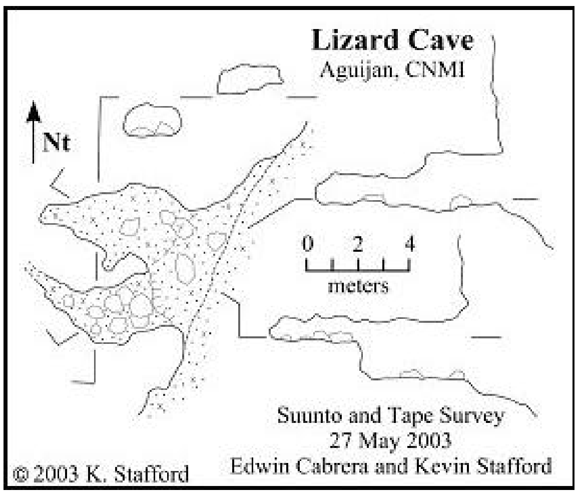

Figure 102: Map of Lizard Cave

Natural Arch Cave

Natural Arch Cave is a flank margin cave, developed in Mariana Limestone (QTmu), approximately 5 meters high on the scarp face in the southwest region of the Middle Terrace. It consists of a large entrance that is 18 meters wide and 8 meters tall with two passages extending to the north. The northeast passage extends inland for 4 meters, while the northwest passage extends inland 8 meters before intersecting a fracture-controlled passage 12 meters long that is oriented at 35°. The floor is composed primarily of alluvium in the entrance area with elevated levels containing bedrock floors. The fracture-controlled passage and the entrance passage leading to it, contain some minor guano deposits mixed with alluvium. The name of the cave is derived from a bedrock arch, 20 to 50 centimeters in diameter, that extends from the west wall of the inland passage.

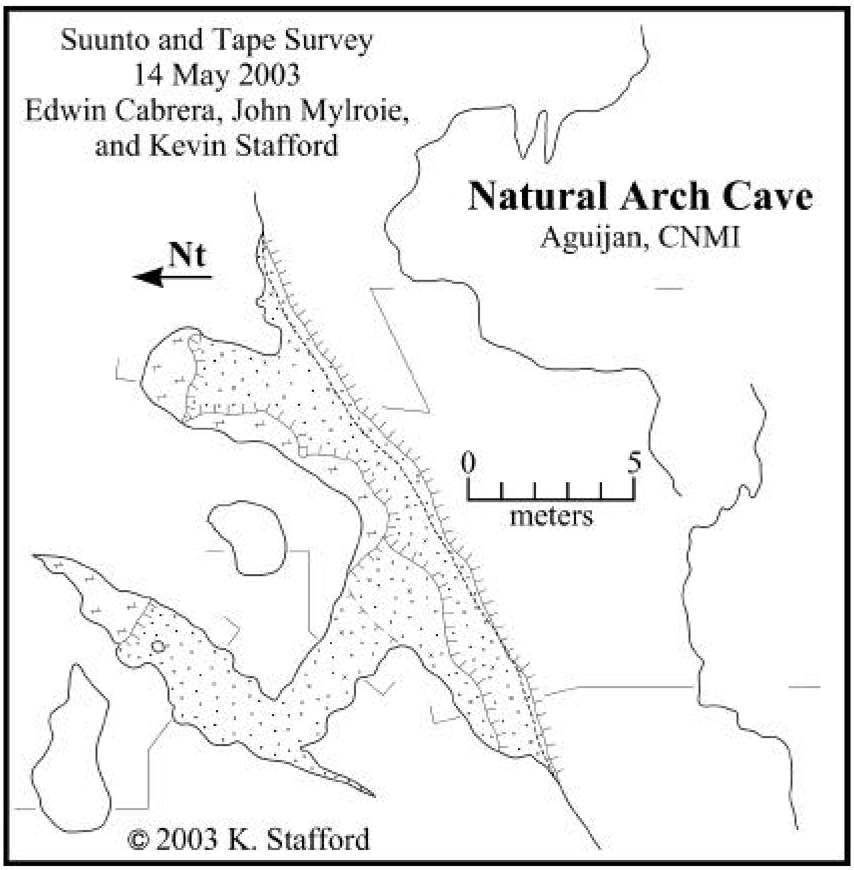

Figure 103: Map of Natural Arch Cave

Scorpion Cave

Scorpion Cave is a small flank margin cave located in the north-central region of the Middle Terrace in the Mariana Limestone (QTmu). It extends inland 11 meters with a maximum width of 9 meters and average ceiling height of 2 meters. The northern and western parts of the cave are slightly elevated with bedrock floors, while the main chamber contains an alluvial floor with three large breakdown blocks. Narrow dissolutional features extend up to two meters into the ceiling in the western part, while a narrow passage extends from the southern edge of the main chamber. The cave was named after a 5 mm long scorpion found during the survey.

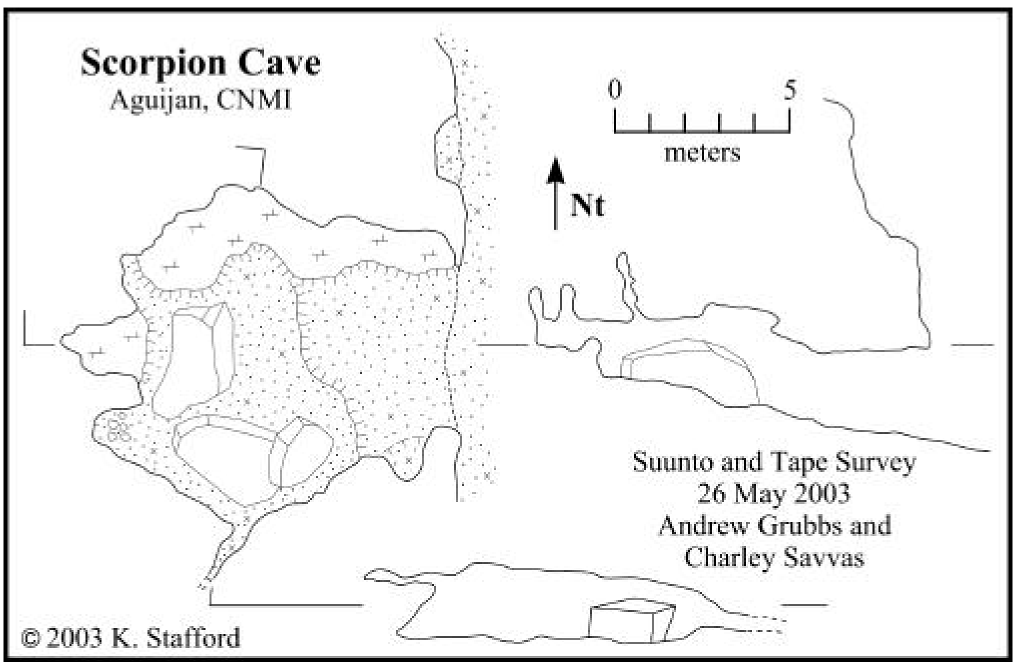

Figure 104: Map of Scorpion Cave

Spider Cave

Spider Cave is a small, breached flank margin cave located in north-central region of the Middle Terrace in the Mariana Limestone (QTmu). The cave has a maximum width of 8 meters exposed along the scarp entrance and extends inland up to 5 meters with a height ranging from 1 to 2 meters. The floor is composed of alluvium and is elevated in the central part of the opening and in the western part of the cave. The name is derived from several large spiders (~8 centimeters in diameter) that were present in the cave at the time of survey.

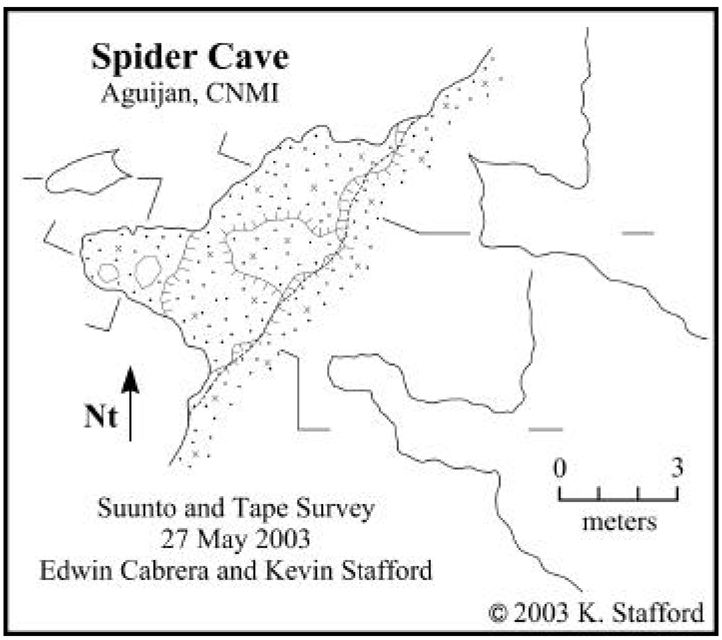

Figure 105: Map of Spider Cave

Swarming Termites Cave

Swarming Termites Cave is a breached, flank margin cave in the eastern region of the Middle Terrace in the Mariana Limestone (QTmu). The cave consists of three main parts, which extend from a 9-meter wide entrance. The northeast portion is a small chamber extending 3 meters inland, the north-central portion is a small passage extending 8 meters inland, and the southern portion is a small passage extending 13 meters inland. All three parts about 3 meters high at the entrance, reducing down to about 1-meter inland. The floor is composed of alluvium with scattered breakdown blocks. The cave appears to be the remnants of a larger flank margin cave, representing the "fingers" that would have extended off of the main chamber of the original cave. The cave is named after the large quantities of termites that were swarming in the region in the early evening.

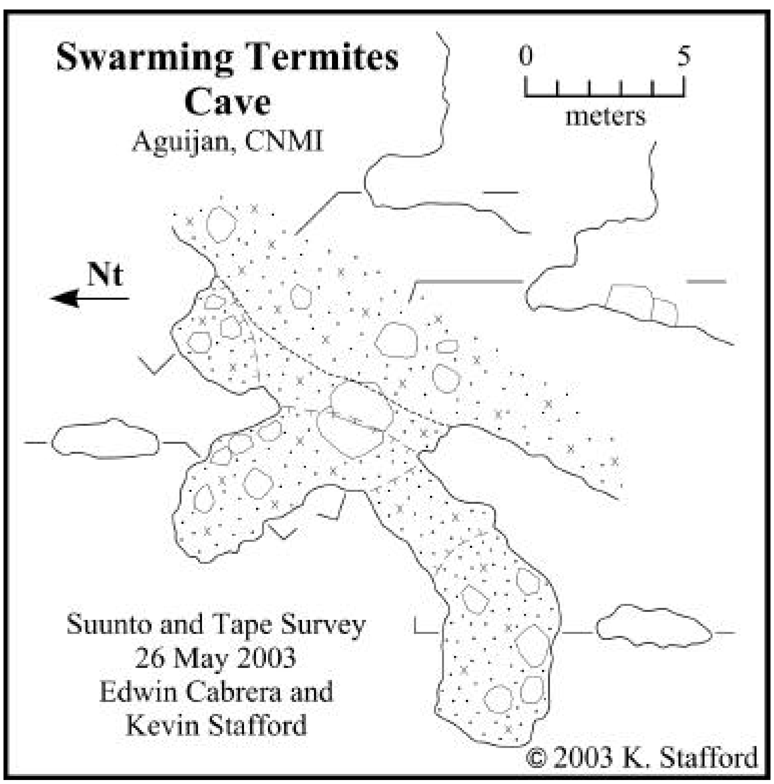

Figure 106: Map of Swarming Termites Cave

Tridactid Cave Complex

Tridactid Cave Complex is located in the eastern region of the Middle Terrace in the Mariana Limestone (QTmu). It is composed of a series of flank margin caves that have been breached by scarp retreat. The features located in the southern part of the complex are shallow and extend inland less than 5 meters with an average height of 3 to 4 meters. In the northern part there is a larger flank margin remnant, which extends inland 35 meters and has bedrock columns dividing the entrance area. This larger remnant averages 1 to 2 meters tall and contains large amounts of breakdown in the middle of the chamber. The larger chamber is connected by a 2-meter deep ledge to a second passage that extends inland 20 meters with a ceiling height of 10 meters created by a floor drop of 8 meters. In the central region there is a split-level flank margin remnant, with a lower level that extends inland 8 meters and an upper level that extends inland 20 meters. The upper level contains two pits, which connected to small chambers that appear to have been partially excavated. In these excavated areas there are several well-worn, tridactid clamshells that appear to have been used for digging the poorly lithified bedrock walls and floor, thus giving the cave complex its name. Based on the proximity of the caves and their corresponding driplines, it is likely that most of these remnant flank margin caves where connected as one single cave in the past and have been separated by scarp retreat.

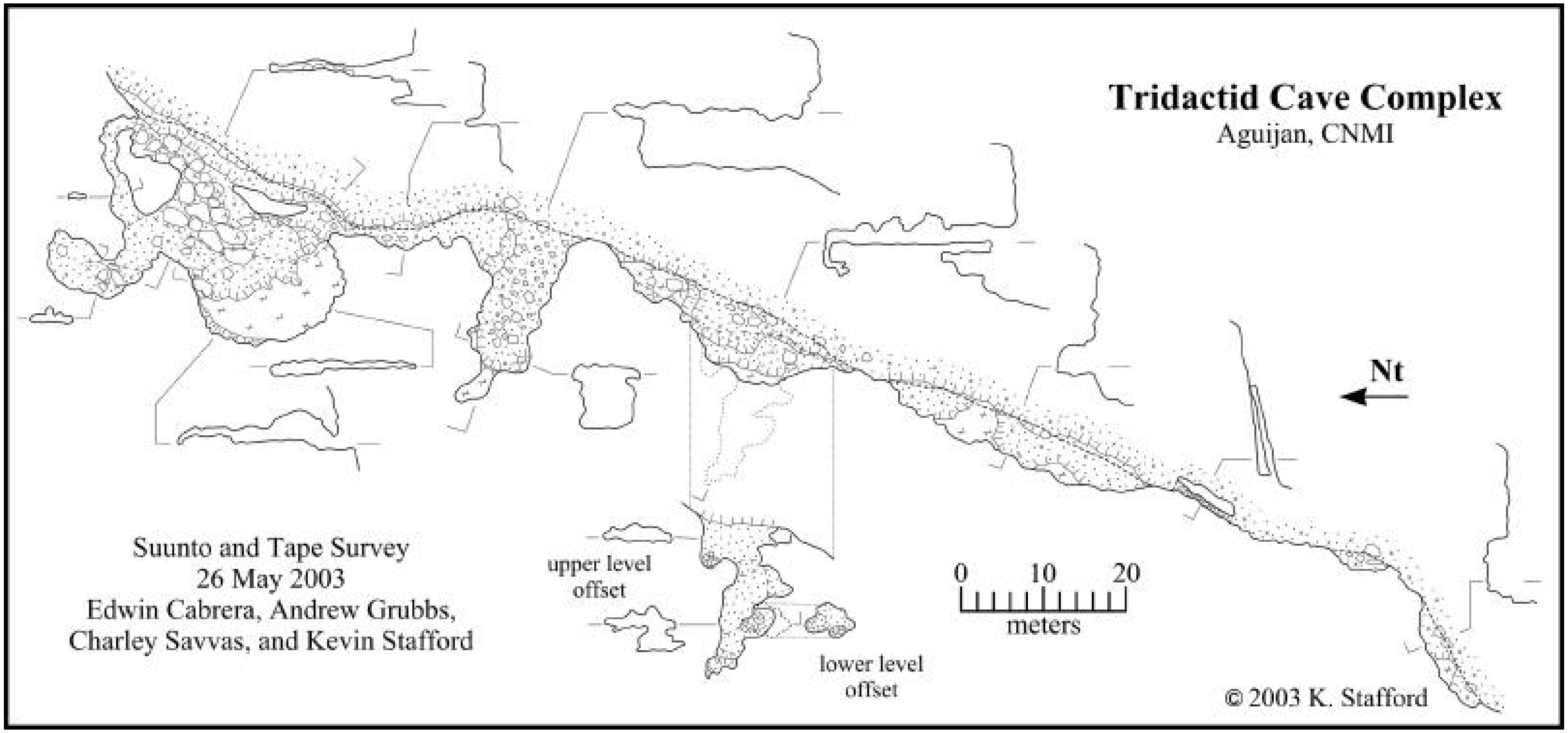

Figure 107: Map of Tridactid Cave Complex.

Waypoint Cave

Waypoint Cave is a small, flank margin cave located in the eastern region of the Middle Terrace in the Mariana Limestone (QTmu). It consists of a small chamber, 5 meters wide and 1.5 meters tall, that has two scarp entrances on the east side and two small passages extending from the west side, with the entrances and passages roughly aligned. The floor consists of alluvium with minor breakdown blocks in the main chamber and a bedrock floor in the northern entrance passage.

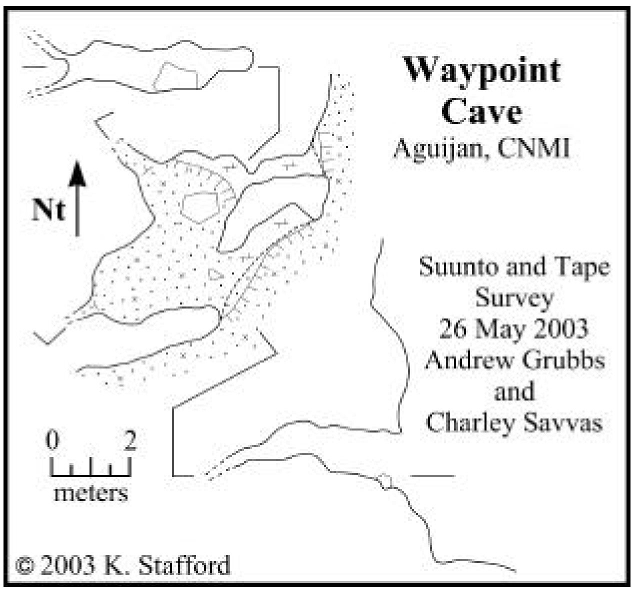

Figure 108: Map of Waypoint Cave

Mixing-Zone Fracture Caves

Insect Bat Cave

Insect Bat Cave is located on the southwest side of the Middle Terrace in the Mariana Limestone (QTmu). It is developed along a fracture trending 120^{o} and extends inland 30 meters with two distinct levels. The upper level is approximately 15 meters above the land surface and averages 3 meters in width, with a narrow slot in the floor that connects to the lower level, which has an average width of 2 meters. A small passage extends to the northeast for 5 meters from the lower level with an average width of 1.5 meters. The feature appears similar to sea-level fracture caves that discharge freshwater and is interpreted as representing a paleo-discharge feature that developed along a fracture.

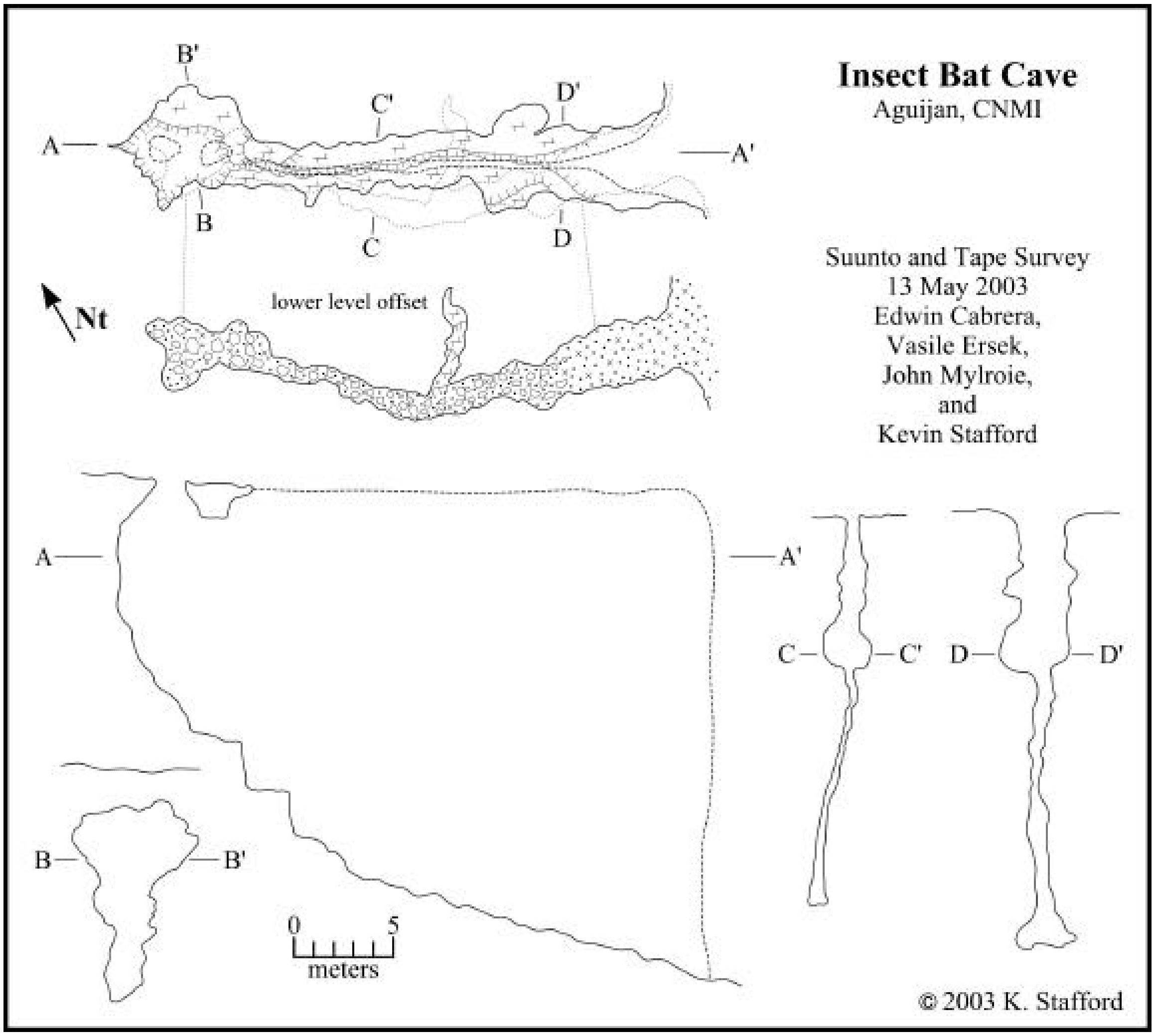

Figure 109: Map of Insect Bat Cave

Toppled Column Cave

Toppled Column Cave is formed along a fracture oriented at 5^{o} in the southwest region of the Middle Terrace. It is developed in the Mariana Limestone (QTmu) and extends inland 23 meters with an average width of 2.5 meters. The feature is 8 meters tall in the entrance and decreases to 5 meters inland. The floor is composed of alluvium and large breakdown blocks in the entrance area and composed of bedrock in the inland part where the floor is elevated. The feature is similar to fracture-controlled, fresh-water discharge features seen at sea level on Tinian and is interpreted as a paleo-discharge feature. The cave is named for the large, broken stalagmite that is wedged in the passage near the entrance.

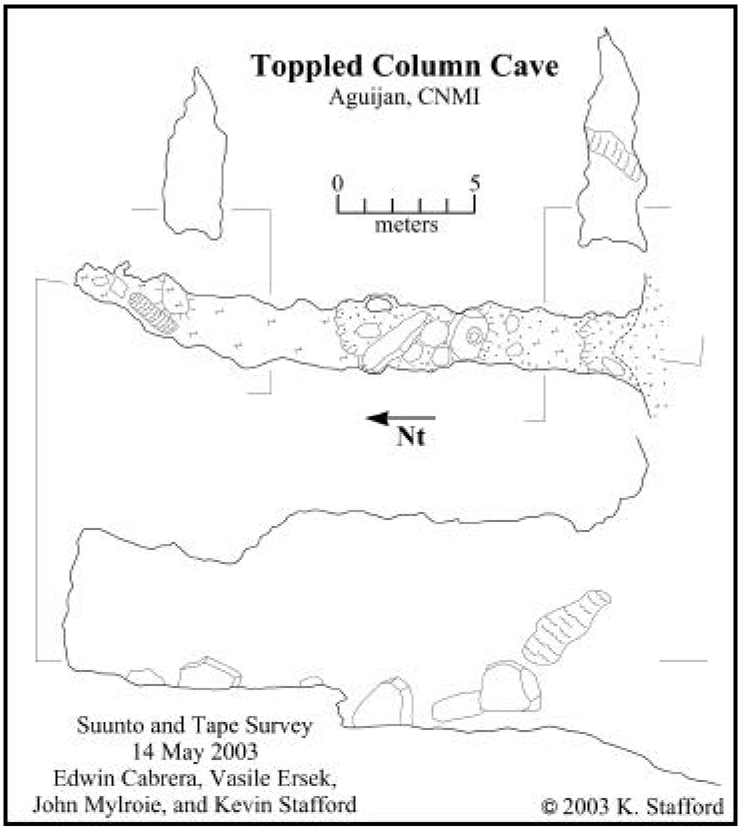

Figure 110: Map of Toppled Column Cave

UPPER TERRACE

Banana Holes

Booney Bee Sink

Booney Bee Sink is a small banana hole type cave located in the northwest region of the Upper Terrace in the Mariana Limestone (QTmu). It is 1 meter wide, 4 meters long and up to 1 meter tall, with a floor composed of alluvium and a small passage continuing from the southeast corner of the cave. This feature appears to take some local recharge when precipitation exceeds local infiltration rates, but the area affected appears to be limited to a few square meters.

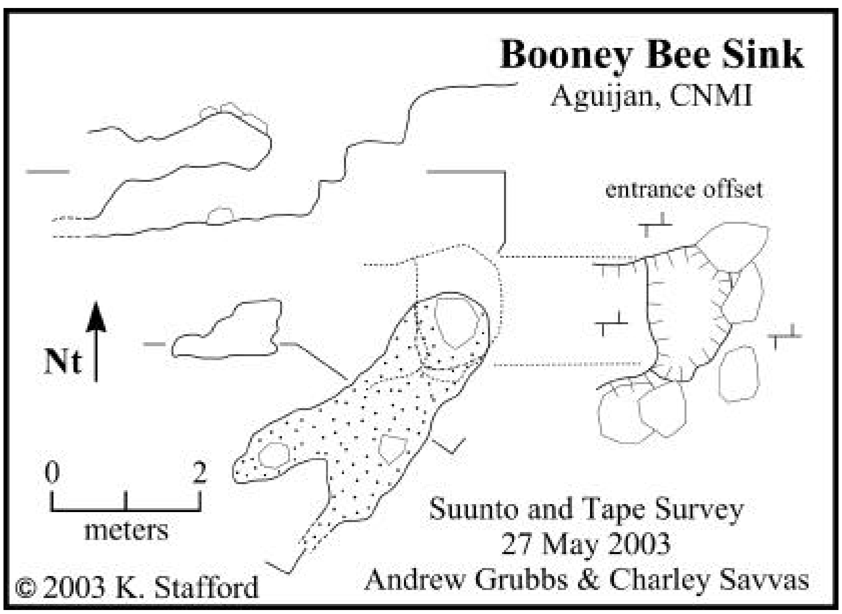

Figure 111: Map of Booney Bee Sink

Dove Cave

Dove Cave is a small banana hole type cave located in the northwest portion of the Upper Terrace in the Mariana Limestone (QTmu). It has a maximum width of 6 meters and an average height of 1 meter, with a floor primarily composed of alluvium and detritus. In the northeast portion of the cave, a flowstone mound is present which is 1 meter by 2 meters and rises 0.5 meters above the floor level of the cave. The entrance is located on the southern side of the feature in a region composed of breakdown blocks, which partially conceal the entrance.

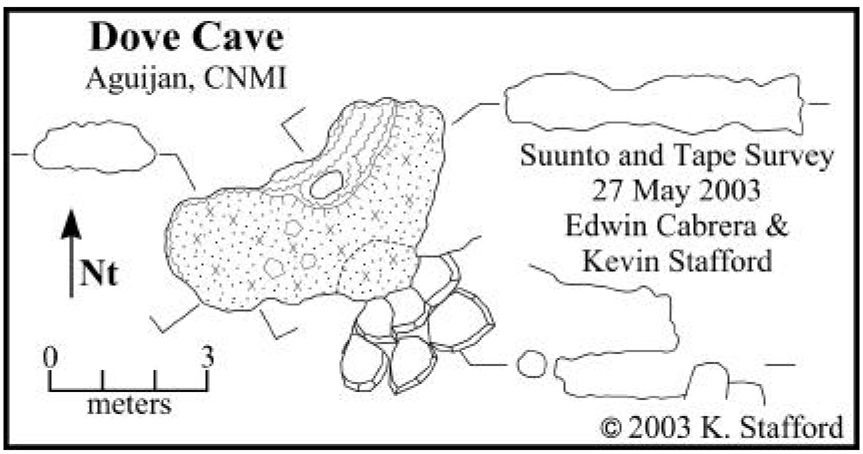

Figure 112: Map of Dove Cave

Fissure Cave

Anvil Cave

Anvil Cave is a fracture cave developed from scarp failure in the northwest region of the Upper Terrace. It is developed in the Mariana Limestone (QTmu) along a fracture strike of 45°. The cave consists of two primary levels. The upper level is partially roofed, 10 meters long and 3 meters wide with a bedrock shelf extending 2 meters to the northwest. The lower level averages 3 meters in width and drops steeply to the northeast over a breakdown floor, with a small breakdown chamber located to the west. The cave continues as a 5 meter wide, 9 meter deep, alluvium floored canyon to the northeast, connecting the Upper and Middle Terraces. The cave contains minor speleothem deposits and is composed primarily of breakdown with enhanced dissolution along the fracture trend and shows evidence of military occupation and modification.

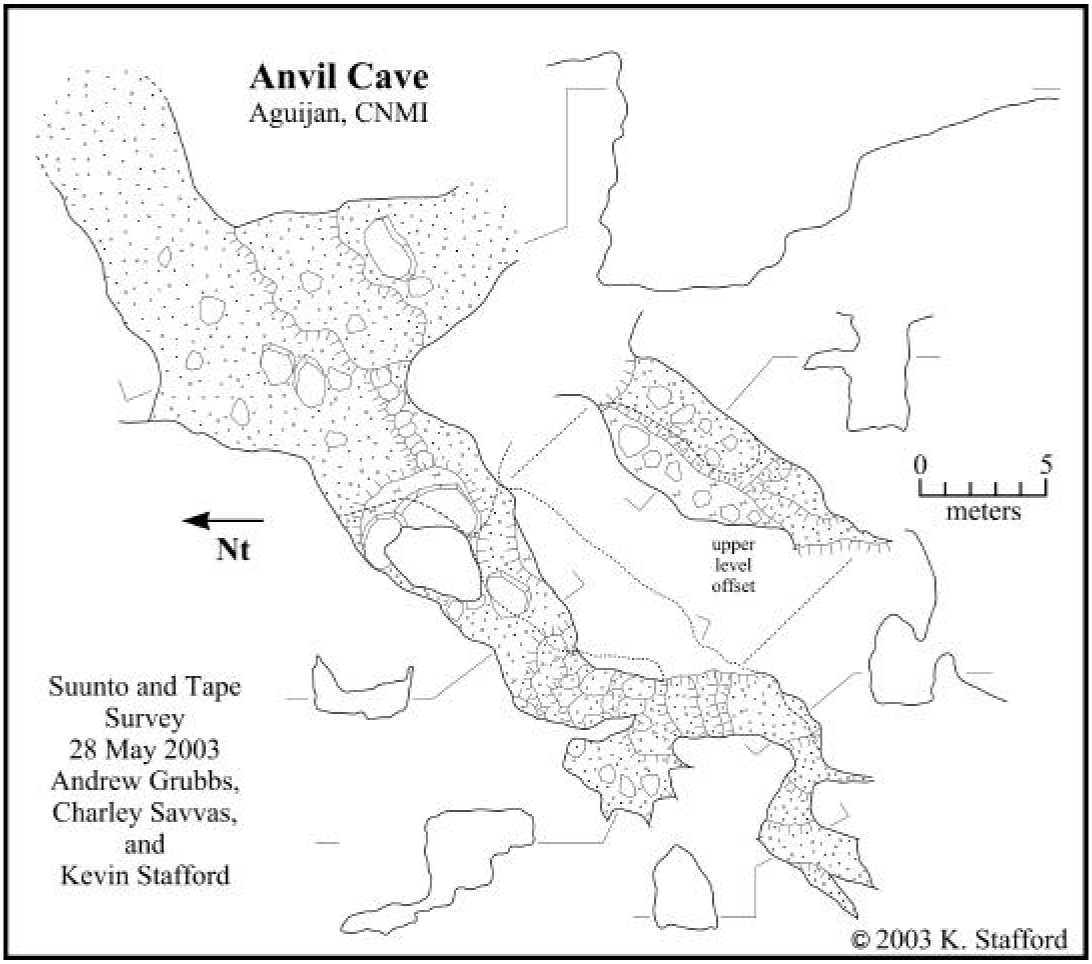

Figure 113: Map of Anvil Cave

Flank Margin Caves

Almost Cave

Almost cave is a small, breached, flank margin cave located in the northwest region of the Upper Terrace in the Mariana Limestone (QTmu). The cave consists of two levels offset approximately 1 meter with a total width of 3 meters and depth of 1.5 meters. The cave is located 2 meters high on a small scarp with two entrances separated by a bedrock column. The cave has no speleothems and the floor is covered with alluvium.

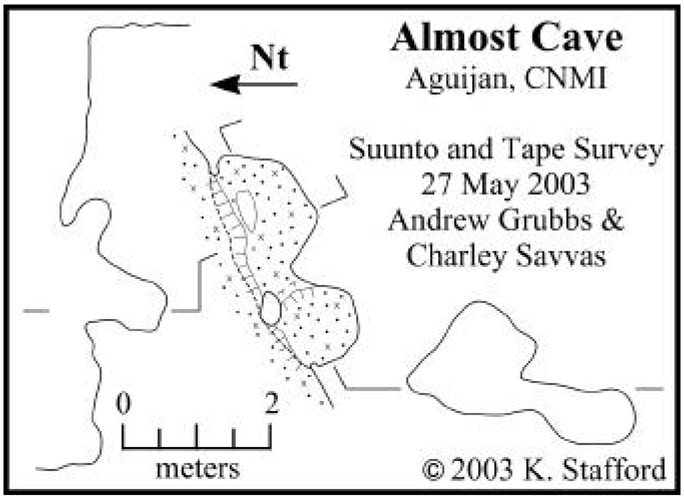

Figure 114: Map of Almost Cave

Biting Mosquitoes Cave

Biting Mosquitoes Cave is a small, breached flank margin cave located in the northwest region of the Upper Terrace in the Mariana Limestone (QTmu). It consists of a single chamber 8 meters wide and 10 meters deep with an average ceiling height of 1.5 meters. The floor is primarily composed of alluvium, but speleothem deposits are present in the northwest portion of the cave, forming a large flowstone mound. There is a collapsed, man-made wall in the entrance of the cave.

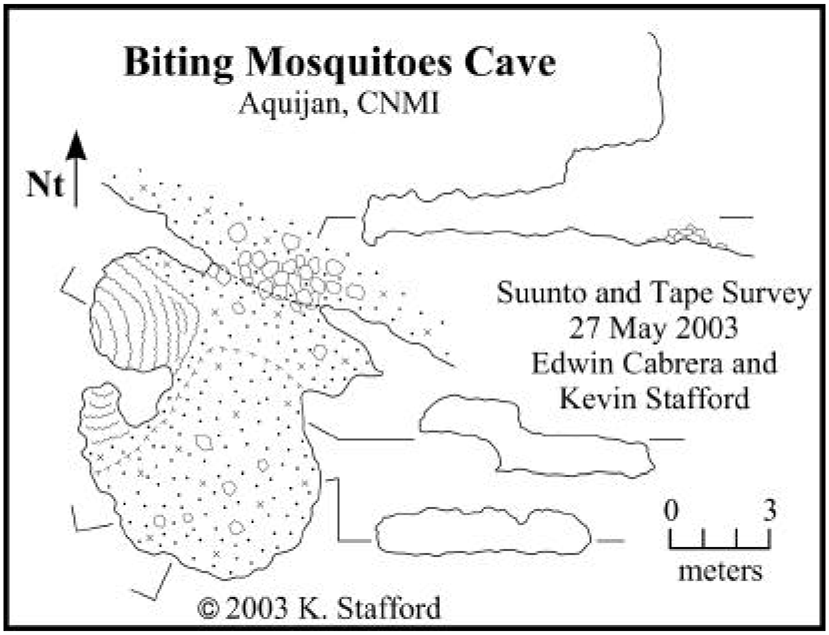

Figure 115: Map of Biting Mosquitoes Cave

Isotope Cave

Isotope Cave is a flank margin cave located in the northwest region of the Upper Terrace in the Mariana Limestone (QTmu). It covers an area of 15 by 23 meters, with two entrances and a large chamber. The two entrances located in the southern portion of the cave connect through 1-meter a tall passage that averages 3 meters wide with alluvium floors. At the junction of the two entrance passages, the cave is 5 meters wide and 2.5 meters tall and dips to the north, where the cave continues and turns north through a 2 meter wide, 1.5 meter tall passage that connects to the main chamber. The main chamber is 10 by 15 meters with and average ceiling height of 3 meters and numerous large breakdown blocks covering the floor. In the southern portion of the main chamber, extensive deposits of flowstone cover the floor and walls, while stalactites cover the ceiling and several stalagmites line the southeast wall. The northern portion of the main chamber is approximately 2 meters tall, but appears much shallower because of the numerous large breakdown blocks that fill the area. In the far northeast part of the cave a small, 5-meter long, 1-meter tall passage in the breakdown can be reached by a short downclimb. The cave is named for several large (1.5 meter tall), "broomstick" stalagmites, which were located and appear ideal for U/Th isotope analysis for age dating.

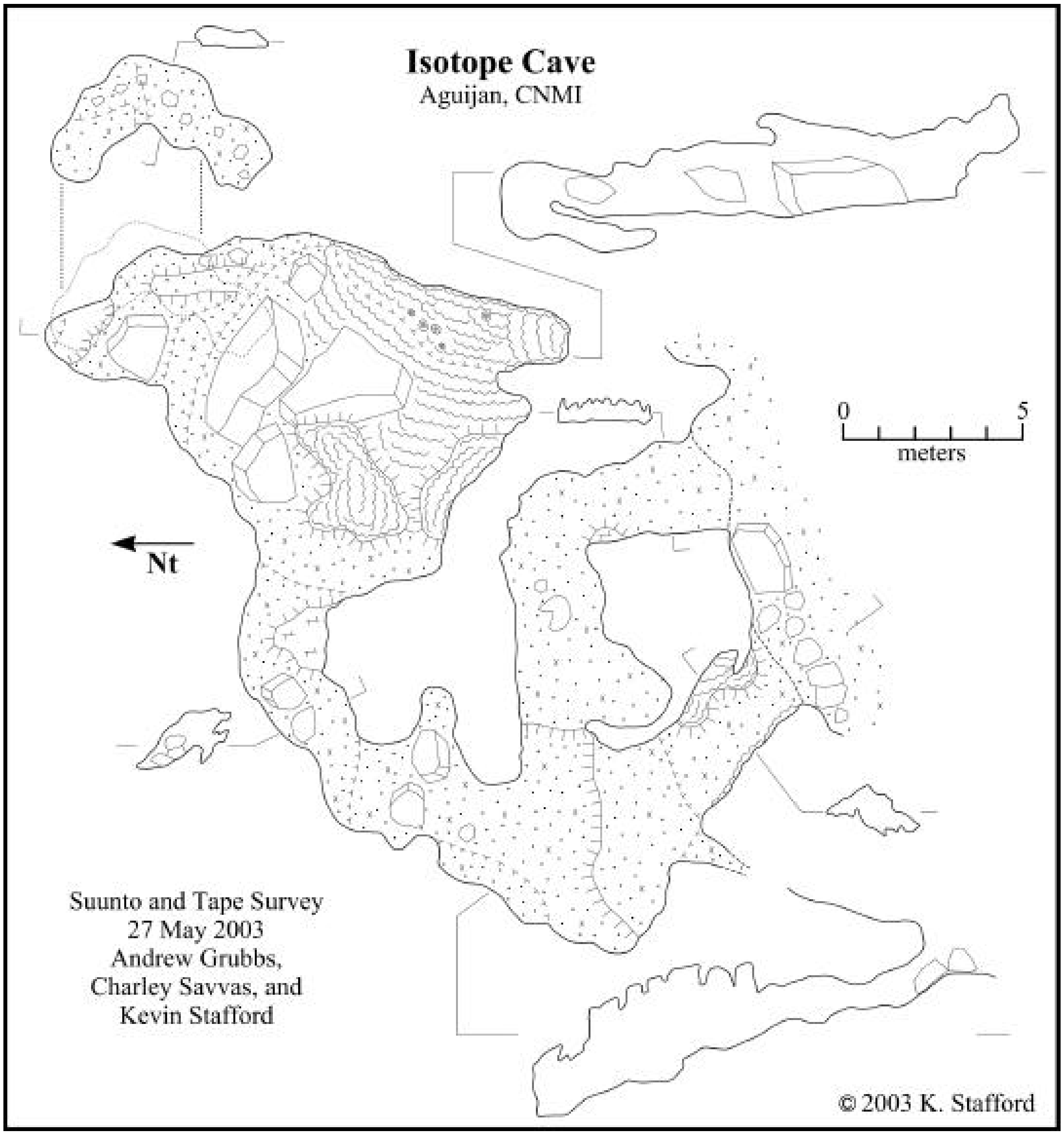

Figure 116: Map of Isotope Cave

Pepper Cave

Pepper Cave is a small flank margin cave located in the northwest portion of the Upper Terrace in the Mariana Limestone (QTmu). It consists of a single chamber 5 meters wide, 3 meters deep and less than 2 meters tall. The floor is composed of alluvium and minor human modification consisting of a 6-meter long rock wall, which extends from the northern side of the entrance to the southeast.

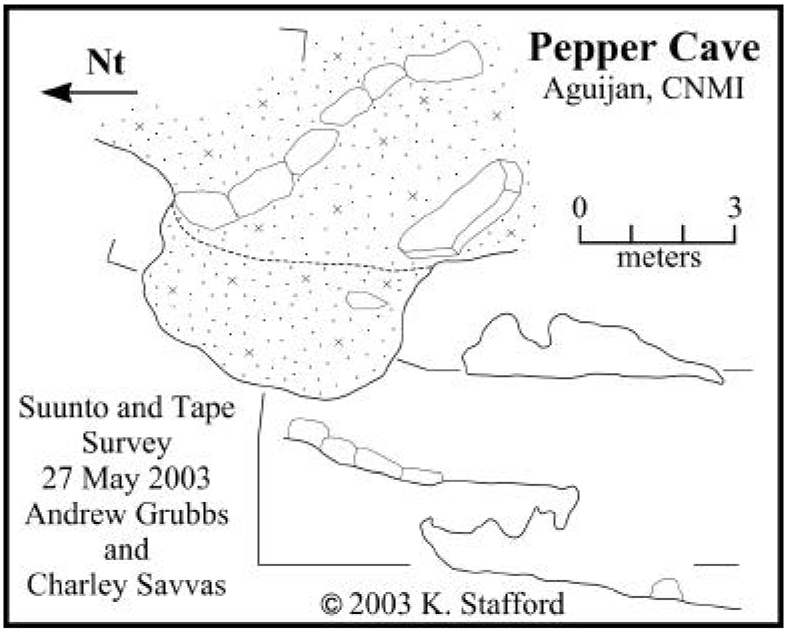

Figure 117: Map of Pepper Cave

Screaming Bat Cave

Screaming Bat Cave consists of two flank margin cave remnants in the northwest region of the Upper Terrace in the Mariana Limestone (QTmu). Both cave remnants extend to the west approximately 5 meters, with an average width of 2 meters. The floor in the northern cave remnant is primarily alluvium, while the floor in the southern cave remnant is primarily bedrock. The name of the cave is derived from fruit bats that were feeding on breadfruit trees in the region at the time of survey.

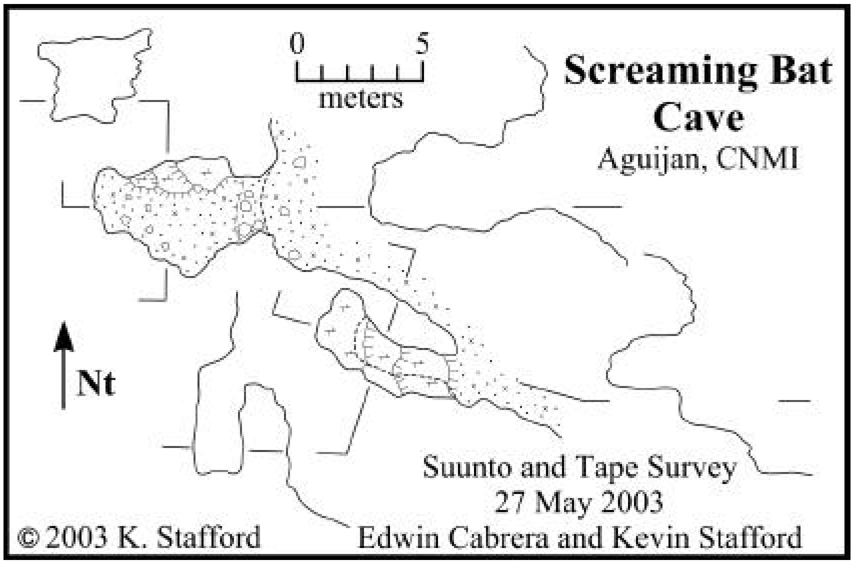

Figure 118: Map of Screaming Bat Cave

APPENDIX B

CAVE AND KARST INVENTORY OF GUAM

MAPS AND DESCRIPTIONS

The following data, with the exception of Asiga Water Caves, Gumayas Cave, and Gadao's Cave, is used with permission from Taborosi (2000). Asiga Water Caves, Gumays Cave and Gadao's Cave descriptions and maps were taken from Taborosi (2004). The data has been organized alphabetically by province and karst feature type. The only changes made were minor spelling and grammatical corrections, and removal of references to figures, color plates and pictures specific to the original document. Table 16 shows the described and mapped karst features of Guam in alphabetical order, Table 17 shows the described and mapped karst features of Guam alphabetically within karst feature type, and Table 18 shows them alphabetically within the province. For ease of use, these three tables include the page number that the karst feature's map and description starts. An additional table (Table 19) at the end of Appendix B shows all of the karst features of Guam sorted alphabetically by name.

Table 16: Karst features of Guam alphabetically

Feature Name	Feature Type	Province	Page Number
Adjoulan Point Cave, Asquirogo Cave, Matala Caves, and Tres Botsas	Flank Margin Caves	Southern Coast	310
Alamagosa Cave	Stream Caves	Southern Mountain Range	321
Amantes Cliff Caves	Flank Margin Caves	Northern Plateau	271
Anae Caverns	Flank Margin Caves	Southern Mountain Range	319
Asanite Cave	Flank Margin Caves	Southern Coast	310
Awesome Cave	Contact Cabes	Northern Plateau	
Awesome Sink	Closed Depressions	Northern Plateau	248
Barragada Sink	Abandoned Stream Caves	Northern Plateau	240
Bay Rum Cave	Mixing-Zone Fracture Caves	Southern Interior Basin	313
Blue Hole	Flank Margin Caves	Southern Coast	312
Carino Sink	Closed Depressions	Northern Plateau	249
Carino Sink Cave	Abandoned Stream Caves	Northern Plateau	240
Castro's Cave	Flank Margin Caves	Northern Plateau	271
Chalan Pago Uvala	Closed Depressions	Northern Plateau	249
Coconut Crab (Ayuyu) Cave	Discharge Features	Northern Plateau	267
Dededo Gulf Course Ponding Basin	Closed Depressions	Northern Plateau	251
Devil's Punchbowl	Flank Margin Caves	Northern Plateau	272
Double Reef Arch	Flank Margin Caves	Northern Plateau	272
Fadian Fish Hatchery Cave	Flank Margin Caves	Northern Plateau	272
Fafai Cave	Flank Margin Caves	Northern Plateau	274
Fena Sinkhole Cave	Stream Caves	Southern Interior Basin	313

Table 16 (continued)

Feature Name	Feature Type	Province	Page Number
Finagayan Banana Hole	Banana Hole	Northern Plateau	241
Frankie's Cave	Flank Margin Caves	Northern Plateau	275
Gayinero Sinks	Closed Depressions	Northern Plateau	251
Gayinero Sinks	Closed Depressions	Northern Plateau	252
Guacluluyau Sink (north)	Closed Depressions	Northern Plateau	251
Gumayas Caves	Abandoned Stream Caves	Southern Coast	305
Haputo, Pinate and Hawaiian Sinkholes	Closed Depressions	Northern Plateau	252
Harmon Sink	Closed Depressions	Northern Plateau	254
Interesting Sink	Closed Depressions	Northern Plateau	256
Ito and Minagawa Sink	Banana Hole	Southern Coast	308
Janum Spring	Discharge Features	Northern Plateau	269
Japanese Caves	Mixing-Zone Fracture Caves	Southern Mountain Range	319
Joan's Cave	Flank Margin Caves	Northern Plateau	281
Joe Quitigua's Water Cave	Flank Margin Caves	Northern Plateau	281
Lafac Grotto	Flank Margin Caves	Northern Plateau	282
Lafac-Anao Collapse 3	Caves of Unknown Origin	Northern Plateau	303
Liyang Almagosa Gelagu	Abandoned Stream Caves	Southern Mountain Range	315
Lost River Rise Cliff Cave	Stream Caves	Southern Interior Basin	314
Marbo Cave	Flank Margin Caves	Northern Plateau	283
Mata Caves	Flank Margin Caves	Southern Coast	311
Mataguac Mud Cave	Stream Caves	Northern Plateau	301
Mataguac Spring Cave	Discharge Features	Northern Plateau	269
Mataguac Spring Sink	Closed Depressions	Northern Plateau	257
Matt's (Matt's Freshwater) Cave	Flank Margin Caves	Northern Plateau	286
Menpachi Fracture	Mixing-Zone Fracture Caves	Northern Plateau	296
Nimitz Hill Collapse Sink #1	Abandoned Stream Caves	Southern Mountain Range	315
Nimitz Hill Collapse Sink #2	Abandoned Stream Caves	Southern Mountain Range	317
Nimitz Hill Shelter Caves	Caves of Unknown Origin	Southern Mountain Range	322
No Can Fracture	Mixing-Zone Fracture Caves	Northern Plateau	298
North Mataguac Cave	Stream Caves	Northern Plateau	303

Table 16 (continued)

Feature Name	Feature Type	Province	Page Number
Orote Grottos	Flank Margin Caves	Southern Coast	311
Orote Window	Flank Margin Caves	Southern Coast	311
Pagat and Haya Pagat Caves	Flank Margin Caves	Northern Plateau	278
Pagat Sea Arch	Caves of Unknown Origin	Northern Plateau	303
Piggy Cave	Contact Cabes	Northern Plateau	
Pinate Sinks	Closed Depressions	Northern Plateau	258
Ritidian Beach Caves	Flank Margin Caves	Northern Plateau	287
Ritidian Cave	Flank Margin Caves	Northern Plateau	290
Ritidian View Cave	Flank Margin Caves	Northern Plateau	292
Scott's Fracture	Mixing-Zone Fracture Caves	Northern Plateau	300
Talofofo Cave #2	Abandoned Stream Caves	Southern Coast	305
Talofofo Caves	Abandoned Stream Caves	Southern Coast	306
Talofofo Pit Cave	Pit Caves	Southern Coast	312
Tarage Beach View Cave	Flank Margin Caves	Northern Plateau	293
Tarague Copra Cave	Closed Depressions	Northern Plateau	260
Tarague Well #1	Closed Depressions	Northern Plateau	261
Tarague Well #2	Closed Depressions	Northern Plateau	262
Tarague Well #3	Closed Depressions	Northern Plateau	263
Tarague Well #4	Closed Depressions	Northern Plateau	264
Tarague Well #5	Flank Margin Caves	Northern Plateau	295
Tarague Well #6, #7, and #8	Closed Depressions	Northern Plateau	266
Two Lovers' Point Pit Cave	Pit Caves	Northern Plateau	300
Yigo Sink	Closed Depressions	Northern Plateau	267

Table 17: Karst features of Guam alphabetically by cave type

Feature Name	Feature Type	Province	Page Number
Barragada Sink	Abandoned Stream Caves	Northern Plateau	240
Carino Sink Cave	Abandoned Stream Caves	Northern Plateau	240
Gumayas Caves	Abandoned Stream Caves	Southern Coast	305
Liyang Almagosa Gelagu	Abandoned Stream Caves	Southern Mountain Range	315
Nimitz Hill Collapse Sink #1	Abandoned Stream Caves	Southern Mountain Range	315
Nimitz Hill Collapse Sink #2	Abandoned Stream Caves	Southern Mountain Range	317
Talofofo Cave #2	Abandoned Stream Caves	Southern Coast	305
Talofofo Caves	Abandoned Stream Caves	Southern Coast	306
Finagayan Banana Hole	Banana Hole	Northern Plateau	241
Ito and Minagawa Sink	Banana Hole	Southern Coast	308
Lafac-Anao Collapse 3	Caves of Unknown Origin	Northern Plateau	303
Nimitz Hill Shelter Caves	Caves of Unknown Origin	Southern Mountain Range	322
Pagat Sea Arch	Caves of Unknown Origin	Northern Plateau	303
Awesome Sink	Closed Depressions	Northern Plateau	248
Carino Sink	Closed Depressions	Northern Plateau	249
Chalan Pago Uvala	Closed Depressions	Northern Plateau	249
Dededo Gulf Course Ponding Basin	Closed Depressions	Northern Plateau	251
Gayinero Sinks	Closed Depressions	Northern Plateau	251
Gayinero Sinks	Closed Depressions	Northern Plateau	252
Guacluluyau Sink (north)	Closed Depressions	Northern Plateau	251
Haputo, Pinate and Hawaiian Sinkholes	Closed Depressions	Northern Plateau	252

Table 17 (continued)

Feature Name	Feature Type	Province	Page Number
Harmon Sink	Closed Depressions	Northern Plateau	254
Interesting Sink	Closed Depressions	Northern Plateau	256
Mataguac Spring Sink	Closed Depressions	Northern Plateau	257
Pinate Sinks	Closed Depressions	Northern Plateau	258
Tarague Copra Cave	Closed Depressions	Northern Plateau	260
Tarague Well #1	Closed Depressions	Northern Plateau	261
Tarague Well #2	Closed Depressions	Northern Plateau	262
Tarague Well #3	Closed Depressions	Northern Plateau	263
Tarague Well #4	Closed Depressions	Northern Plateau	264
Tarague Well #6, #7, and #8	Closed Depressions	Northern Plateau	266
Yigo Sink	Closed Depressions	Northern Plateau	267
Awesome Cave	Contact Cabes	Northern Plateau	
Piggy Cave	Contact Cabes	Northern Plateau	
Coconut Crab (Ayuyu) Cave	Discharge Features	Northern Plateau	267
Janum Spring	Discharge Features	Northern Plateau	269
Mataguac Spring Cave	Discharge Features	Northern Plateau	269
Adjoulan Point Cave, Asquirogo Cave, Matala Caves, and Tres Botsas	Flank Margin Caves	Southern Coast	310
Amantes Cliff Caves	Flank Margin Caves	Northern Plateau	271
Anae Caverns	Flank Margin Caves	Southern Mountain Range	319
Asanite Cave	Flank Margin Caves	Southern Coast	310
Blue Hole	Flank Margin Caves	Southern Coast	312
Castro's Cave	Flank Margin Caves	Northern Plateau	271
Devil's Punchbowl	Flank Margin Caves	Northern Plateau	272

Table 17 (continued)

Feature Name	Feature Type	Province	Page Number
Double Reef Arch	Flank Margin Caves	Northern Plateau	272
Fadian Fish Hatchery Cave	Flank Margin Caves	Northern Plateau	272
Fafai Cave	Flank Margin Caves	Northern Plateau	274
Frankie's Cave	Flank Margin Caves	Northern Plateau	275
Joan's Cave	Flank Margin Caves	Northern Plateau	281
Joe Quitigua's Water Cave	Flank Margin Caves	Northern Plateau	281
Lafac Grotto	Flank Margin Caves	Northern Plateau	282
Marbo Cave	Flank Margin Caves	Northern Plateau	283
Mata Caves	Flank Margin Caves	Southern Coast	311
Matt's (Matt's Freshwater) Cave	Flank Margin Caves	Northern Plateau	286
Orote Grottos	Flank Margin Caves	Southern Coast	311
Orote Window	Flank Margin Caves	Southern Coast	311
Pagat and Haya Pagat Caves	Flank Margin Caves	Northern Plateau	278
Ritidian Beach Caves	Flank Margin Caves	Northern Plateau	287
Ritidian Cave	Flank Margin Caves	Northern Plateau	290
Ritidian View Cave	Flank Margin Caves	Northern Plateau	292
Tarage Beach View Cave	Flank Margin Caves	Northern Plateau	293
Tarague Well #5	Flank Margin Caves	Northern Plateau	295
Bay Rum Cave	Mixing-Zone Fracture Caves	Southern Interior Basin	313
Japanese Caves	Mixing-Zone Fracture Caves	Southern Mountain Range	319
Menpachi Fracture	Mixing-Zone Fracture Caves	Northern Plateau	296
No Can Fracture	Mixing-Zone Fracture Caves	Northern Plateau	298
Scott's Fracture	Mixing-Zone Fracture Caves	Northern Plateau	300
Talofofo Pit Cave	Pit Caves	Southern Coast	312
Two Lovers' Point Pit Cave	Pit Caves	Northern Plateau	300
Alamagosa Cave	Stream Caves	Southern Mountain Range	321
Fena Sinkhole Cave	Stream Caves	Southern Interior Basin	313
Lost River Rise Cliff Cave	Stream Caves	Southern Interior Basin	314
Mataguac Mud Cave	Stream Caves	Northern Plateau	301
North Mataguac Cave	Stream Caves	Northern Plateau	303

Table 18: Karst features of Guam alphabetically by province

Feature Name	Feature Type	Province	Page Number
Amantes Cliff Caves	Flank Margin Caves	Northern Plateau	271
Awesome Cave	Contact Cabes	Northern Plateau	
Awesome Sink	Closed Depressions	Northern Plateau	248
Barragada Sink	Abandoned Stream Caves	Northern Plateau	240
Carino Sink	Closed Depressions	Northern Plateau	249
Carino Sink Cave	Abandoned Stream Caves	Northern Plateau	240
Castro's Cave	Flank Margin Caves	Northern Plateau	271
Chalan Pago Uvala	Closed Depressions	Northern Plateau	249
Coconut Crab (Ayuyu) Cave	Discharge Features	Northern Plateau	267
Dededo Gulf Course Ponding Basin	Closed Depressions	Northern Plateau	251
Devil's Punchbowl	Flank Margin Caves	Northern Plateau	272
Double Reef Arch	Flank Margin Caves	Northern Plateau	272
Fadian Fish Hatchery Cave	Flank Margin Caves	Northern Plateau	272
Fafai Cave	Flank Margin Caves	Northern Plateau	274
Finagayan Banana Hole	Banana Hole	Northern Plateau	241
Frankie's Cave	Flank Margin Caves	Northern Plateau	275
Gayinero Sinks	Closed Depressions	Northern Plateau	251
Gayinero Sinks	Closed Depressions	Northern Plateau	252
Guacluluyau Sink (north)	Closed Depressions	Northern Plateau	251
Haputo, Pinate and Hawaiian Sinkholes	Closed Depressions	Northern Plateau	252
Harmon Sink	Closed Depressions	Northern Plateau	254
Interesting Sink	Closed Depressions	Northern Plateau	256

Table 18 (continued)

Feature Name	Feature Type	Province	Page Number
Janum Spring	Discharge Features	Northern Plateau	269
Joan's Cave	Flank Margin Caves	Northern Plateau	281
Joe Quitigua's Water Cave	Flank Margin Caves	Northern Plateau	281
Lafac Grotto	Flank Margin Caves	Northern Plateau	282
Lafac-Anao Collapse 3	Caves of Unknown Origin	Northern Plateau	303
Marbo Cave	Flank Margin Caves	Northern Plateau	283
Mataguac Mud Cave	Stream Caves	Northern Plateau	301
Mataguac Spring Cave	Discharge Features	Northern Plateau	269
Mataguac Spring Sink	Closed Depressions	Northern Plateau	257
Matt's (Matt's Freshwater) Cave	Flank Margin Caves	Northern Plateau	286
Menpachi Fracture	Mixing-Zone Fracture Caves	Northern Plateau	296
No Can Fracture	Mixing-Zone Fracture Caves	Northern Plateau	298
North Mataguac Cave	Stream Caves	Northern Plateau	303
Pagat and Haya Pagat Caves	Flank Margin Caves	Northern Plateau	278
Pagat Sea Arch	Caves of Unknown Origin	Northern Plateau	303
Piggy Cave	Contact Cabes	Northern Plateau	
Pinate Sinks	Closed Depressions	Northern Plateau	258
Ritidian Beach Caves	Flank Margin Caves	Northern Plateau	287
Ritidian Cave	Flank Margin Caves	Northern Plateau	290
Ritidian View Cave	Flank Margin Caves	Northern Plateau	292
Scott's Fracture	Mixing-Zone Fracture Caves	Northern Plateau	300
Tarage Beach View Cave	Flank Margin Caves	Northern Plateau	293
Tarague Copra Cave	Closed Depressions	Northern Plateau	260

Table 18 (continued)

Feature Name	Feature Type	Province	Page Number
Tarague Well #1	Closed Depressions	Northern Plateau	261
Tarague Well #2	Closed Depressions	Northern Plateau	262
Tarague Well #3	Closed Depressions	Northern Plateau	263
Tarague Well #4	Closed Depressions	Northern Plateau	264
Tarague Well #5	Flank Margin Caves	Northern Plateau	295
Tarague Well #6, #7, and #8	Closed Depressions	Northern Plateau	266
Two Lovers' Point Pit Cave	Pit Caves	Northern Plateau	300
Yigo Sink	Closed Depressions	Northern Plateau	267
Adjoulan Point Cave, Asquirogo Cave, Matala Caves, and Tres Botsas	Flank Margin Caves	Southern Coast	310
Asanite Cave	Flank Margin Caves	Southern Coast	310
Blue Hole	Flank Margin Caves	Southern Coast	312
Gumayas Caves	Abandoned Stream Caves	Southern Coast	305
Ito and Minagawa Sink	Banana Hole	Southern Coast	308
Mata Caves	Flank Margin Caves	Southern Coast	311
Orote Grottos	Flank Margin Caves	Southern Coast	311
Orote Window	Flank Margin Caves	Southern Coast	311
Talofofo Cave #2	Abandoned Stream Caves	Southern Coast	305
Talofofo Caves	Abandoned Stream Caves	Southern Coast	306
Talofofo Pit Cave	Pit Caves	Southern Coast	312
Bay Rum Cave	Mixing-Zone Fracture Caves	Southern Interior Basin	313
Fena Sinkhole Cave	Stream Caves	Southern Interior Basin	313
Lost River Rise Cliff Cave	Stream Caves	Southern Interior Basin	314

Table 18 (continued)

Feature Name	Feature Type	Province	Page Number
Alamagosa Cave	Stream Caves	Southern Mountain Range	321
Anae Caverns	Flank Margin Caves	Southern Mountain Range	319
Japanese Caves	Mixing-Zone Fracture Caves	Southern Mountain Range	319
Liyang Almagosa Gelagu	Abandoned Stream Caves	Southern Mountain Range	315
Nimitz Hill Collapse Sink #1	Abandoned Stream Caves	Southern Mountain Range	315
Nimitz Hill Collapse Sink #2	Abandoned Stream Caves	Southern Mountain Range	317
Nimitz Hill Shelter Caves	Caves of Unknown Origin	Southern Mountain Range	322

NORTHERN PLATEAU

Abandoned Stream Caves

Barragada Sink

Only two traversable horizontal caves thought to be paleo-phreatic conduits have been identified in the interior of northern Guam away from volcanic inliers. The first [...]

The second such cave is entered through a 10 m deep collapsed Barrigada Sink (a.k.a. Appealing Sink) in Barrigada and also has a traversable length of about 100 meters (C. Wexel, pers. comm.)

Both of these karst features are probably abandoned conduits. Their horizontal orientation and circular cross-sections suggest origin as phreatic conduits developed at or near the water table, subsequently inactivated by the drop in sea level. Sea level drop may also have triggered the collapse and opening of the passages to the surface, once buoyant support by water was removed. Both Carino Sink and Barrigada Sink are presently used for disposal of household waste. Organic decay may be the cause of "bad air" in the passages of Carino Sink Cave.

Carino Sink Cave

Dolines can form by roof collapse of a cave. They tend to be vertical walled but with further collapse may come to closely resemble solution dolines. Collapse dolines are not common on Guam, but do occur in both the coastal lowlands as well as the plateau. In the northern Guam plateau only one vertical-walled collapse doline (Carino

Sink) has been identified, but probably many more exist. Carino Sink is located in Chalan Pago, on a slope of a ridge dividing the large Chalan Pago uvala and Guacluluyao dry valley. It is about 20 meters deep, and has vertical walls and two traversable cave passages leading from its base. The passages could not be explored due to low oxygen conditions from organic decay of large amounts of trash in the sink. A similar feature exists in Barrigada (Barrigada Sink). [...]

Both of these karst features are probably abandoned conduits. Their horizontal orientation and circular cross-sections suggest origin as phreatic conduits developed at or near the water table, subsequently inactivated by the drop in sea level. Sea level drop may also have triggered the collapse and opening of the passages to the surface, once buoyant support by water was removed. Both Carino Sink and Barrigada Sink are presently used for disposal of household waste. Organic decay may be the cause of “bad air” in the passages of Carino Sink Cave.

Banana Holes

Finagayan Banana Hole

The Finagayan Banana Hole is 3 meters deep and circular in plan. Collapse portion of the ceiling is 3 meters in diameter, with the subsurface void reaching about 6 meters in diameter. Central part of the banana hole is filled by collapse rubble, but the periphery contains fine sediment. Walls of the banana hole show pronounced horizontal dissolution planes, and contain stalactites. In a dye trace test in July 1999, dye injected into this banana hole was chased with large amounts of water and was detected at the coast only 4 hours after injection (P. Casey, pers. comm., cited in Mylroie et al., 1999). The sinkhole now receives storm water drainage from the capped Navy's Finagayan landfill.

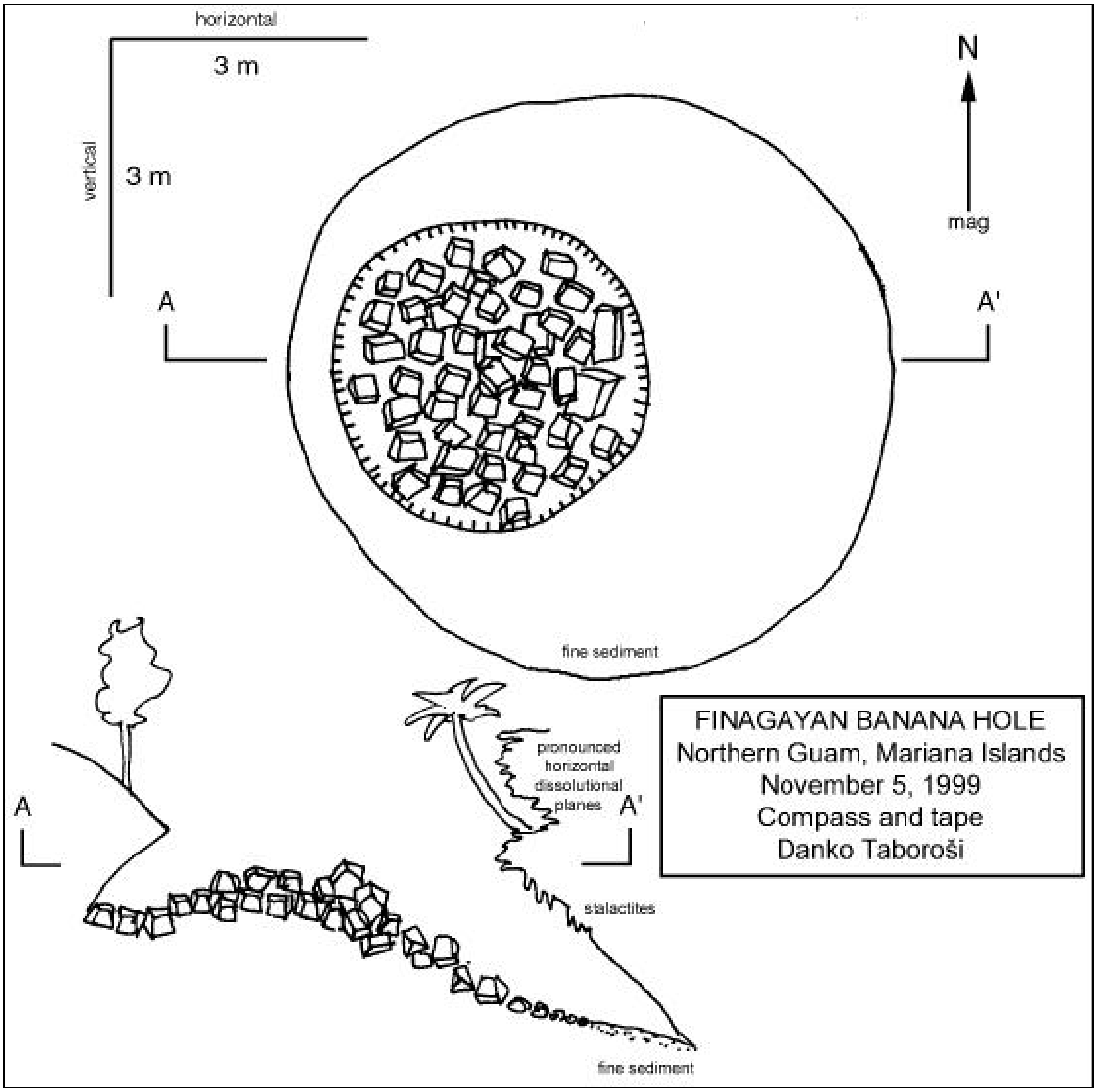

Figure 119: Map of Finagayan Banana Hole

Contact Caves

Awesome Cave

Awesome Cave is another stream cave fed by an allogenic stream originating on the slopes of Mt. Santa Rosa. Located in the southeast of Mt. Santa Rosa, on the volcanic-limestone contact, this cave is entered via a collapse entrance in an allogenic point recharge sinkhole (Awesome Sink). The active swallet of the cave is mud clogged and not traversable. The cave is a series of large chambers (up to 20 m wide and 8 m tall), descending in a step like fashion. Underneath the chambers, a vadose canyon passage developed on the volcanic contact carries an ephemeral allogenic stream. Most of the ceiling of the large chambers is characterized by well-developed phreatic dissolution surfaces. Only in the top chamber, at the cave entrance, is the ceiling collapse in nature, well decorated by small stalactites. The floor here is composed of collapse rubble. The ceiling of the lower (second and third) chambers is generally subparallel to the floor and contains phreatic cusps and smooth surfaces developed across paleosol infill materials. Paleosol infill exposed in the chamber ceiling include matrix-supported and clast-supported breccias, infill of joints and fractures in the bedrock, and soil pipes. Most of the cave floor of the second and third chamber is composed of mud, flowstone, and, along the eastern wall, a series of large rimstone pools. The lowest (fourth) chamber has a horizontal and an extremely flat ceiling, almost completely a result of phreatic dissolution. It also exposes numerous soil breccias and soil-infilled fractures. The floor of this room is mostly made of collapse boulders. In one place in the floor, the underlying vadose stream passage can be entered though an opening in its collapsed roof. The vadose stream passage follows the volcanic contact. The high-energy ephemeral stream has incised into the volcanic bedrock. Passage floor here contains volcanic and limestone fragments, rocks cemented by $CaCO_3$ and soil breccia. The passage can be followed upstream towards the swallet for about 35 meters. Downstream, the passage joins Interesting Cave, another vadose stream coming from a point recharge sinkhole adjacent to Awesome Sink.

Unlike Piggy Cave, where large chambers appear to be a result of collapse, chambers in Awesome Cave appear to be flank margin caves. They could be associated with previous fresh-water lens positions and sea level still-stands. It is also possible that phreatic dissolution features in this cave have developed during flooding episodes when the drainage in the main vadose stream passage was impeded. This complex cave is one of the more spectacular caves in Guam, because of its size, unique speleothems, and historical artifacts found in it.

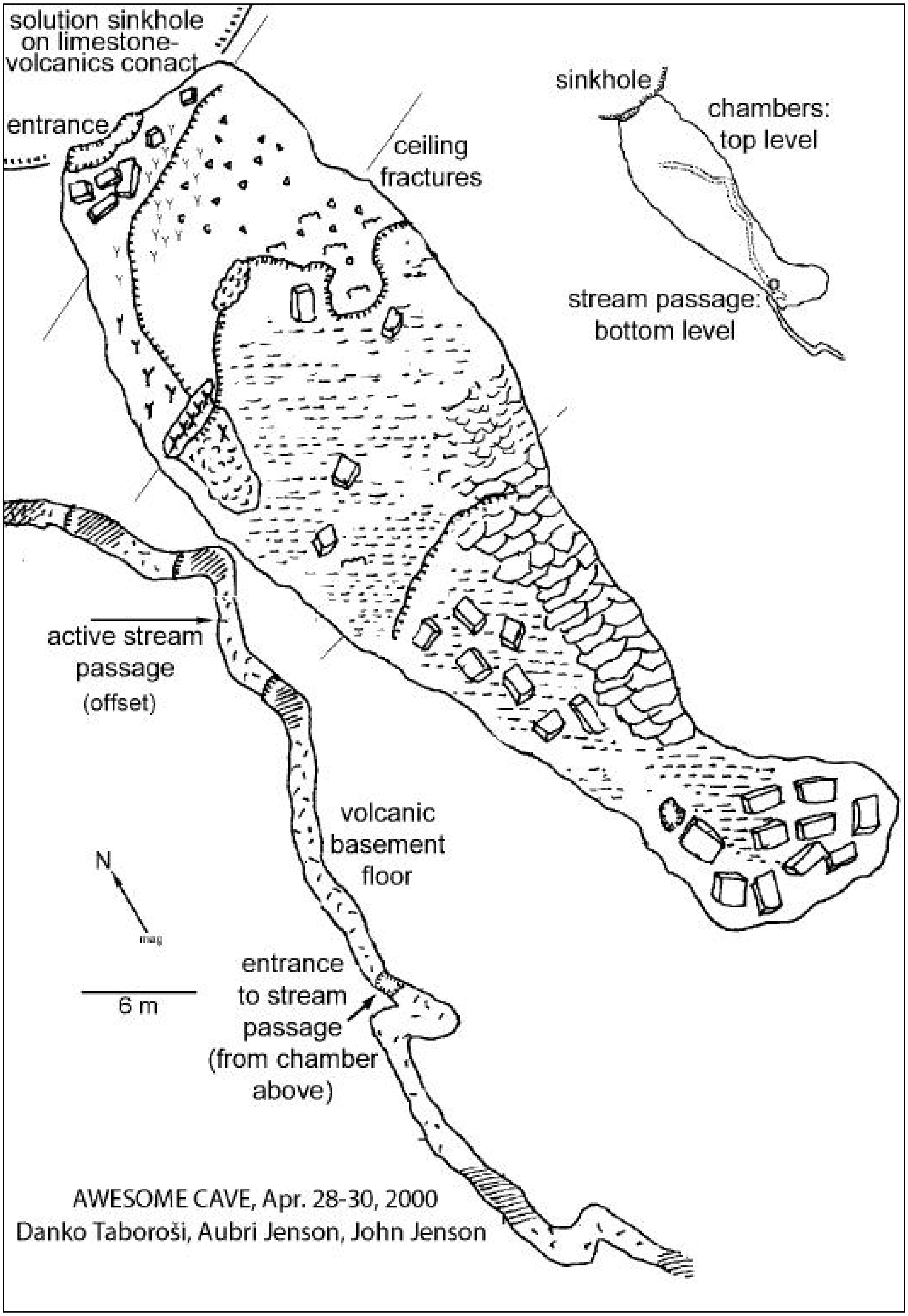

Figure 120: Map of Awesome Cave

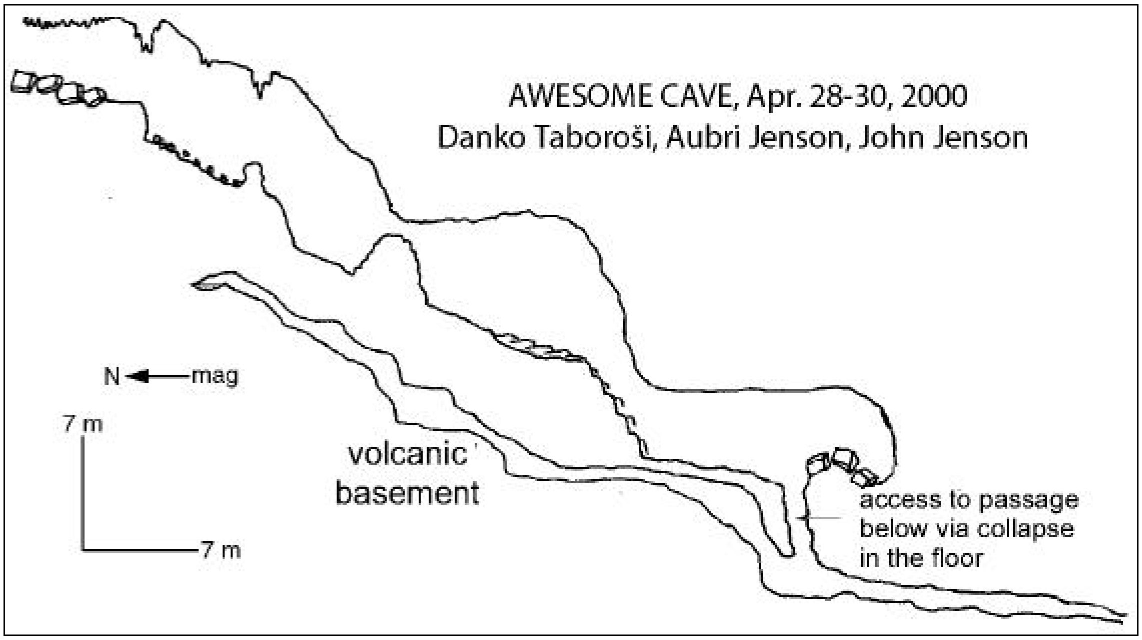

Figure 121: Profile map of Awesome Cave

Piggy Cave

Piggy Cave has developed on the north side of Mt. Santa Rosa. Its main entrance is inside a small doline. The bottom of the doline is alluviated and supports dense wetland vegetation. A puddle few meters in diameter is present even in the dry season. Adjacent to this lowest point in the doline is the main entrance to Piggy Cave, located at the base of an Alifan Limestone hill. The entrance is about 4 meters wide and 2 meters tall, with scattered collapse boulders. A single passage leads from the entrance, following the bedrock basement contact (Plate 17, photo 5). The passage floor is volcanic basement, with volcanic and limestone debris, including volcanic fragments cemented by calcite deposition (Plate 17, photo 6). The passage is an actively down-cutting vadose canyon incised in volcanic rock by an ephemeral stream. The passage contains numerous puddles and pools, even in the dry season. The largest of the pools is more than 2 meters deep. The passage is generally 1-2 m wide and up to a few meters tall. Several steep drop-offs, up to 3 meters tall, become underground waterfalls during rain events. Physical erosion of volcanic bedrock is evident and the stream channel of the main passage has been cut to a meter below the contact with the limestone. The limestone-volcanic contact is clearly visible throughout the main cave passage. Most of this cave is a single narrow stream passage, but several larger rooms have been made by progradational collapse. In such places, it is necessary to walk over the rubble instead of following the vadose stream that has been buried by collapse, before rejoining the stream passage. In collapse rooms, several additional entrances and skylights have been made by ceiling collapse. The stream passage becomes too small to follow after 120 meters from the entrance. The back entrance to the cave is located near the end of traversable stream passage. It is has developed by progradational collapse, to the top of a 9 meter tall vertical passage. This cave is beautifully decorated by stalactites and flowstone banks. Collapse rooms show very little stalactite development. A prominent feature in collapse rooms are vertical flutes in the boulders and walls, made by input of vadose waters flowing through the ceiling. In the upper portions of the cave (the first two collapse rooms) some phreatic dissolution features are identifiable in the walls, but they are not as numerous as in Awesome Cave.

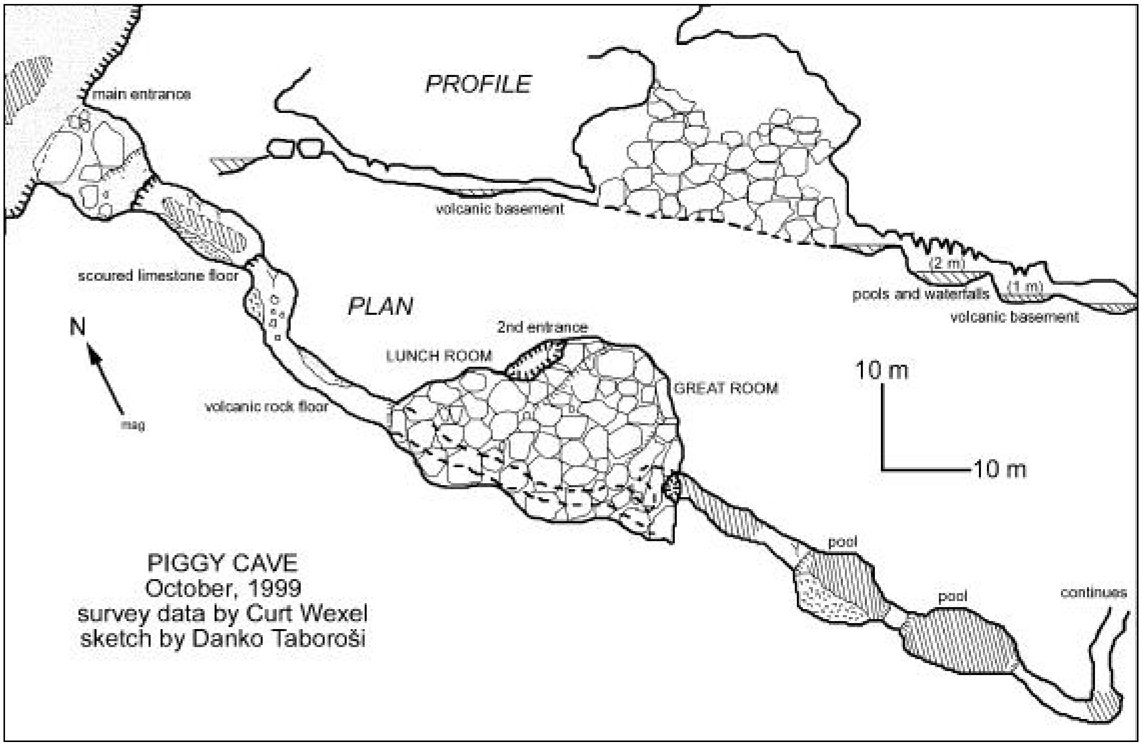

Figure 122: Map of Piggy Cave

Closed Depressions

Awesome Sink

Similar features exist associated with Mt. Santa Rosa, the larger of the two volcanic inliers in northern Guam. Like Mataguac Spring Sink, Awesome and Interesting sinks are located right on the contact between volcanic units and limestone, they are small in area, about 100 and 50 m in diameter and 10 m and 7 meters deep, respectively. They are each fed by a temporary allogenic stream that sinks into mud-filled ponors. There are traversable stream caves associated with the sinkholes, and will be discussed in the next chapter. The caves are not entered via ponors but through nearby collapse entrances.

Carino Sink

Dolines can form by roof collapse of a cave. They tend to be vertical walled but with further collapse may come to closely resemble solution dolines. Collapse dolines are not common on Guam, but do occur in both the coastal lowlands as well as the plateau. In the northern Guam plateau only one vertical-walled collapse doline (Carino Sink) has been identified, but probably many more exist. Carino Sink is located in Chalan Pago, on a slope of a ridge dividing the large Chalan Pago uvala and Guacluluyao dry valley. It is about 20 meters deep, and has vertical walls and two traversable cave passages leading from its base. The passages could not be explored due to low oxygen conditions from organic decay of large amounts of trash in the sink. A similar feature exists in Barrigada (Barrigada Sink).

Chalan Pago Uvala

As individual dolines grow, they may coalesce and form large closed depressions with multiple ponors (White, 1988). Such compound dolines are known as uvalas (Cvijic, 1960).

There are large depressions that look like compound sinkholes scattered throughout the northern Guam plateau. However, as long as their origin is uncertain (i.e., depositional vs. dissolutional), it would be premature to classify them as uvalas.

However, real uvalas certainly exist in the Agana argillaceous member of the Mariana Limestone, which clearly exhibits some classical karst features.

The largest and the most complex internally drained depression here is the Chalan Pago uvala, with its steep and complex, deeply incised slopes. This uvala is clearly a result of surface dissolution. No ponor or cave passages associated with this feature could be identified.

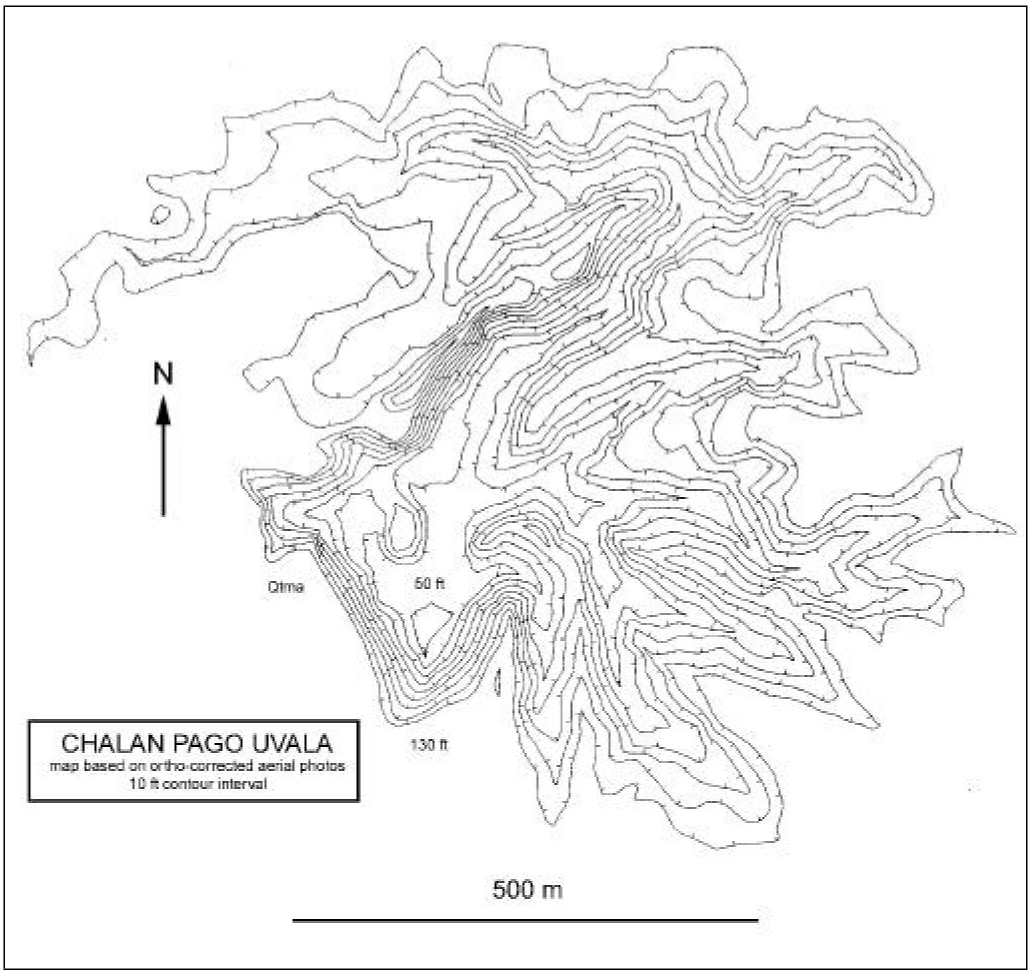

Figure 123: Map of Chalan Pago Uvala

Dededo Gulf Course Ponding Basin

An example of a ponding basin that is certainly a modified natural sinkhole.

Gayinero Sinks

There are two depressions on the southeast flank of Mt. Santa Rosa, collectively known as the Gayinero Sink. The depression to the north appears to be a small border polje. It satisfies all three criteria set forth by Gams (1978) to be considered a polje: 1) flat floor, 2) closed basin with steeply rising marginal slope on at least one side, and 3) karstic drainage. Reaching 400 meters in width, it even satisfies Gams' arbitrary requirement of 400 meters as the minimum width of a polje, although not that of 1 kilometer set by Cvijic (1893).

Guacluluyau Sink (north)

Two dolines in the nearby Guacluluyao dry valley were deemed representative of valley dolines in northern Guam. They are nestled in a dry valley, with valley walls rising about 30 meters. The northern doline is 350 meters long and 50 meters wide. Its floor is flat and covered by alluvium. The periphery of the doline has some exposed limestone and colluvium derived from valley wall collapse. The southern doline is smaller and has been modified by human activities. One part of it has been deepened and serves as a fish pond. The two dolines are separated by a ridge indicating one-time elevation of a valley floor (prior to development of dolines).

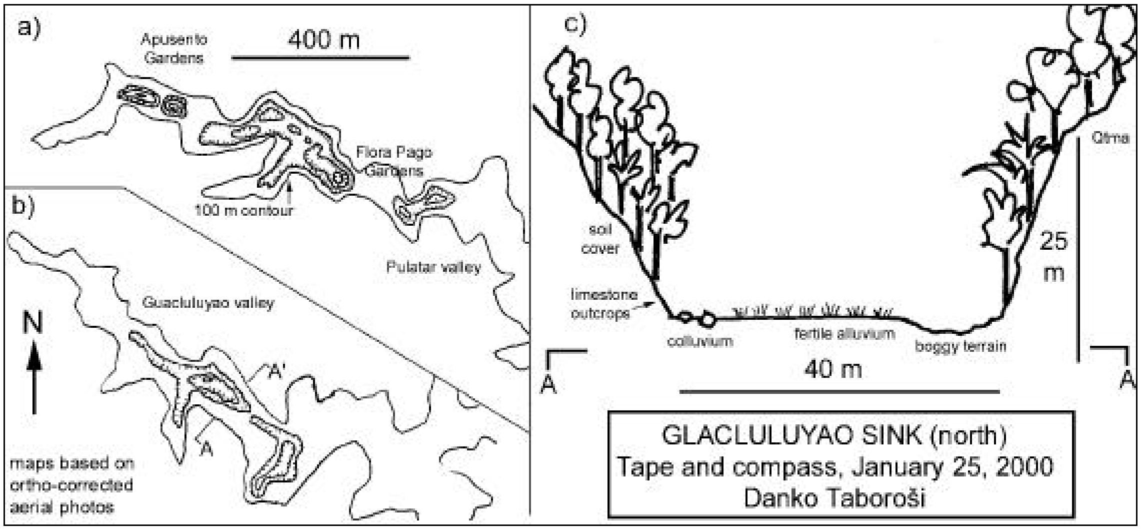

Figure 124: Map of Guacluluyau (Glacluluyu) Sink (north)

Gayinero Sinks

There are two depressions on the southeast flank of Mt. Santa Rosa, collectively known as the Gayinero Sink. The depression to the north appears to be a small border polje. It satisfies all three criteria set forth by Gams (1978) to be considered a polje: 1) flat floor, 2) closed basin with steeply rising marginal slope on at least one side, and 3) karstic drainage. Reaching 400 meters in width, it even satisfies Gams' arbitrary requirement of 400 meters as the minimum width of a polje, although not that of 1 kilometer set by Cvijic (1893).

Haputo, Pinate and Hawaiian Sinkholes

The influence of this mechanism on development of depressions in northern Guam is yet to be examined. There are several clusters of depressions on the northern Guam plateau found near its edge (above Haputo Beach, above Tarague Embayment, and in Pinate area and near the Hawaiian Rock Quarry in Mangilao) that I believe are most likely drawdown dolines. The sinkholes in Pinate are particularly impressive thanks to their close clustering and nearly identical shape and size. This conclusion is based on the following observations: the aforementioned dolines are funnel shaped, deep depressions (up to 30 meters), small in area and circular in plan, with no point recharge. Some evidence of collapse was observed, but this should not be taken as evidence against draw-down origin as most draw-down dolines have an element of rock subsistence or settling in their development (Williams, 1985).

Nevertheless, collapse also should be considered as a potential origin of these depressions. They may be a result of collapse with subsequent breakdown of the sides and filling of the bottom, coming to mimic other non-collapse dolines. It is quite possible that a collapse feature is so completely mantled by soil and debris that it cannot be distinguished from dolines of other origins (White, 1988).

In any case, the dolines described here are true karst features. It is difficult to imagine depressions of such geometry being depositional in nature.

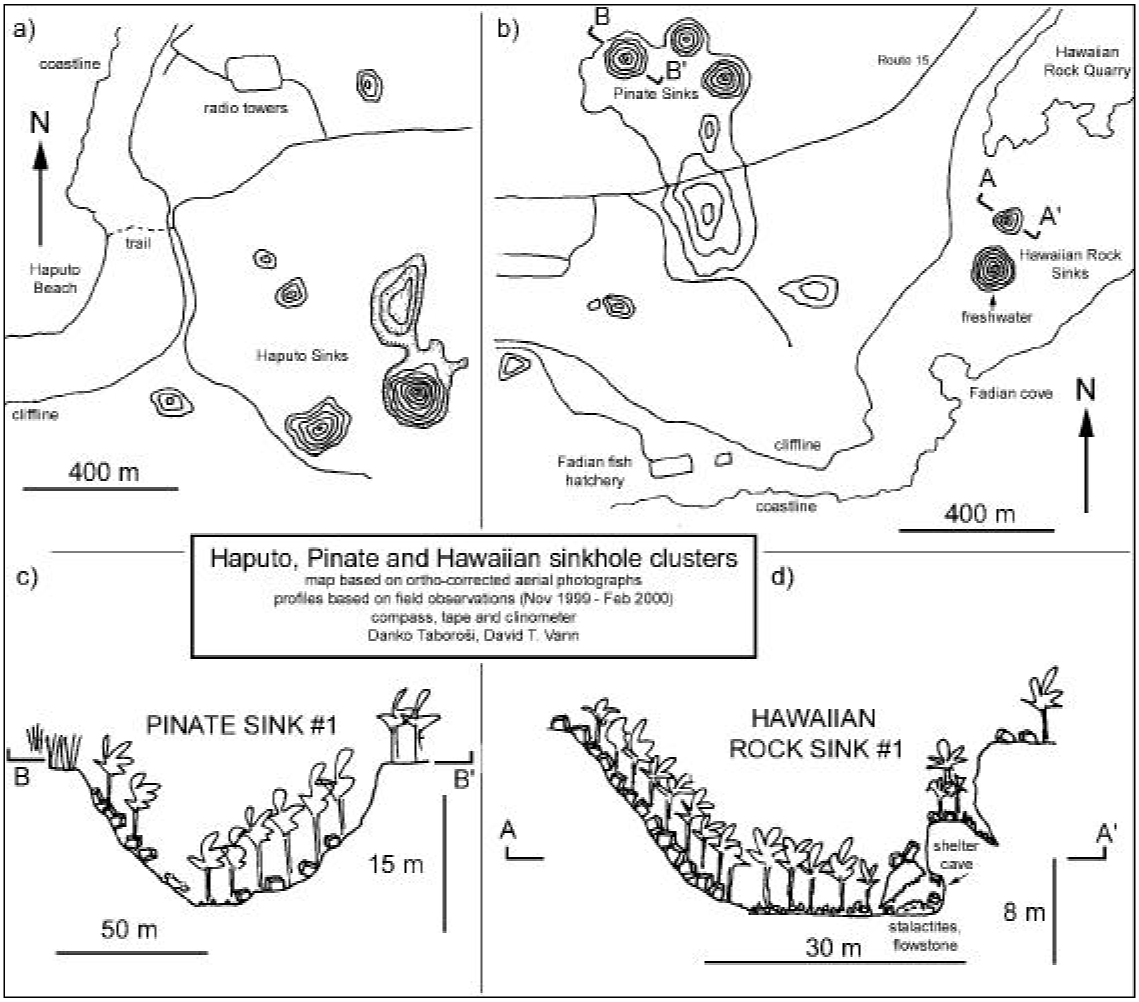

Figure 125: Map of Haputo, Pinate and Hawaiian sinkhole clusters

Harmon Sink

Previous studies have suggested that the Harmon Sink may not be a true dissolutional feature, but a modified depositional depression. In a remedial investigation for ground water restoration, Ogden Environmental and Energy Services Co. (1995) stated that no evidence exists for whether Harmon Sink is a true sinkhole or a depositional depression. They observe that the deepest area of the basin, where drainage must sink, has no discrete sinking point or shaft. However, lack of a visible sinking point should not be taken as evidence against dissolutional origin of Harmon sink. Sinkholes can be covered by soil or waste mantle (Jennings, 1985) and in case of Harmon Sink the accumulations of alluvium and debris in its deepest portion are obvious. The accumulated debris causes frequent perching of water in a pond and probably hides the sinking point in the deepest portion of the depression, which has been blocked off by construction of the Marine Drive.

In conclusion, Harmon Sink appears to be different from other internally drained depressions in northern Guam. It contains the only identified true non-allogenic blind valley in Guam. The valley is well developed and reminiscent of continental karst. It seems to be an old landform, antedating human modification of drainage and urbanization of northern Guam.

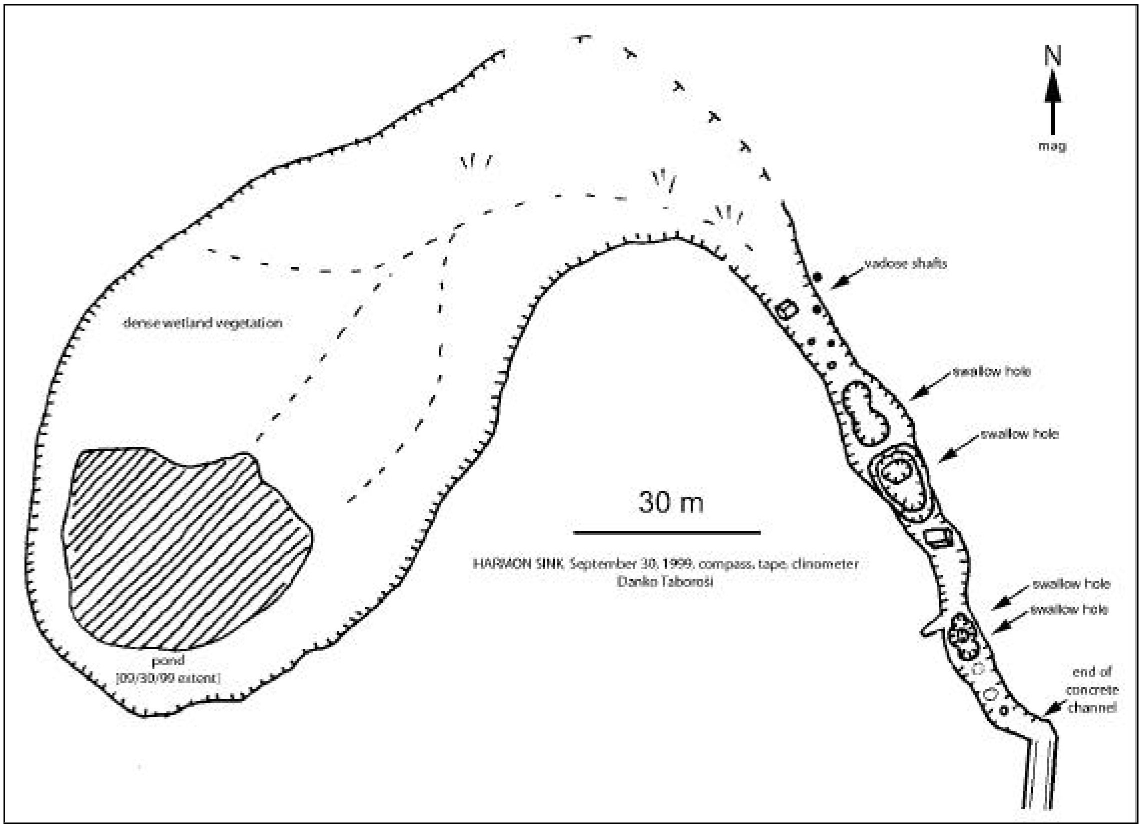

Figure 126: Map of Harmon Sink

Interesting Sink

Similar features exist associated with Mt. Santa Rosa, the larger of the two volcanic inliers in northern Guam. Like Mataguac Spring Sink, Awesome and Interesting sinks are located right on the contact between volcanic units and limestone, they are small in area, about 100 and 50 m in diameter and 10 m and 7 meters deep, respectively. They are each fed by a temporary allogenic stream that sinks into mud-filled ponors. There are traversable stream caves associated with the sinkholes, and will be discussed in the next chapter. The caves are not entered via ponors but through nearby collapse entrances.

Mataguac Spring Sink

Mataguac Spring Sink is a small, deep sink situated at the base of Mataguac Hill, on the contact between Alutom Formation outcrop and the surrounding Mariana Limestone. It has a maximum diameter of 100 meters, and a depth of about 15 meters. The floor of the sink is covered by alluvium derived from the volcanic material, with scattered limestone outcrops and partially exposed volcanic saprolite. Dense hydrophilic vegetation lines the bottom of the sinkhole and a small stream meanders along its bottom. This stream is fed not only by direct allogenic runoff, but also by Mataguac spring, a small ephemeral spring fed by limited water storage in the limestone immediately adjacent to and overlaying the volcanic basement. At the southeastern end of the sink is a distinct ponor, leading to a cave traversable to some 30 meters. Location of Mataguac Spring Sink with respect to neighboring volcanic terrane and a schematic diagram representing its profile are shown in Fig. 7.4-b. There are several other sinkholes surrounding the Mataguac Hill, which are particularly well developed along its northern and southwestern flanks. They contain several contact stream caves and are sites of ephemeral ponds.

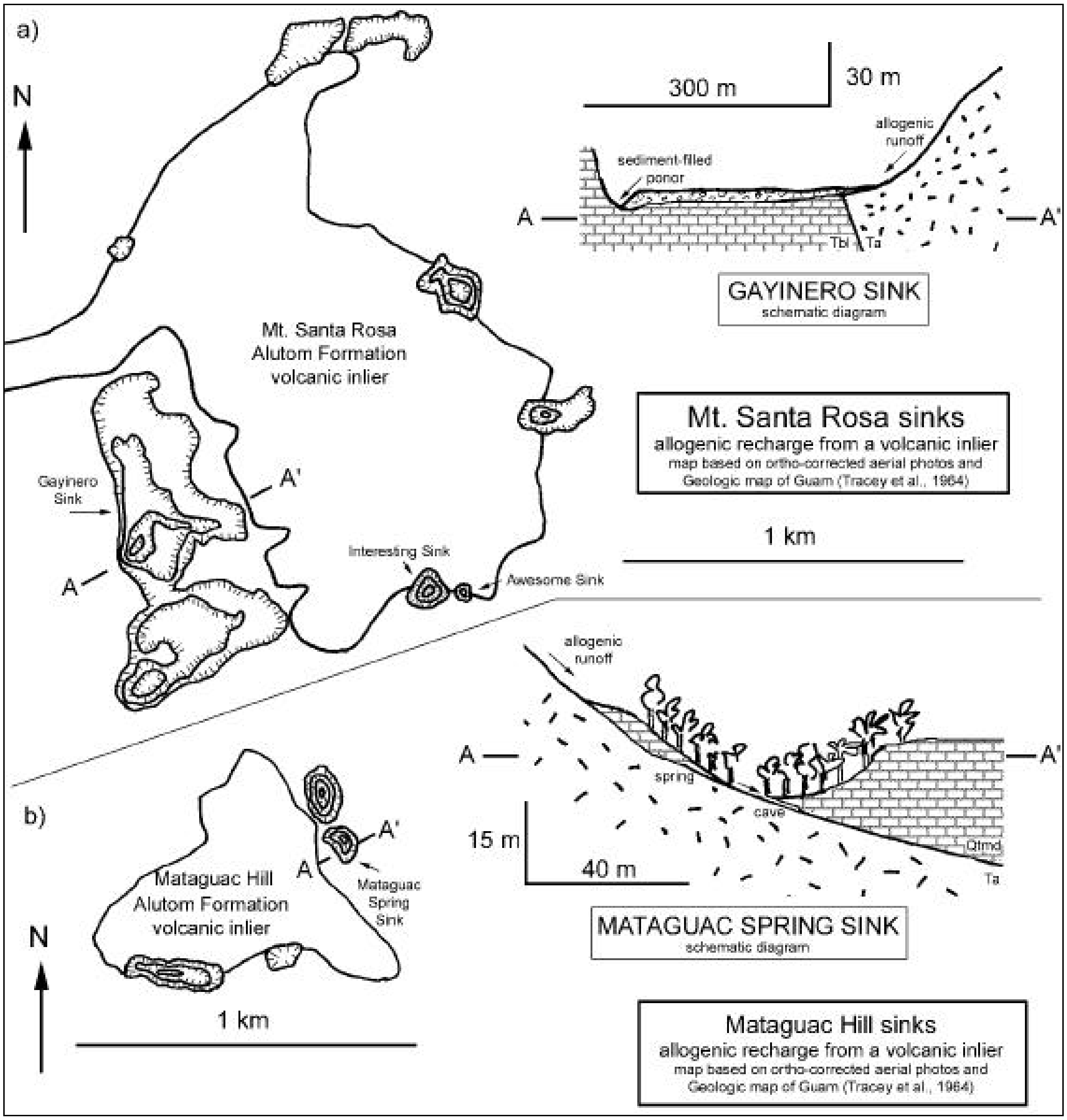

Figure 127: Map of Mt. Santa Rosa Sinks and Mataguac Spring Sink

Pinate Sinks

Drawdown dolines will not develop if vertical hydraulic conductivity is great throughout the vadose zone or if vertical permeability is spatially uniform (Williams, 1985). This is a situation applicable to some raised coral atolls (Ford and Williams, 1989). However, previous studies in northern Guam have documented storage of water in the epikarst over extended periods of time (Jocson et al., 1999) as well as significant lateral movement in the vadose zone (Barner, 1995). Together these observations suggest the existence of the epikarstic water table and distinct permeable vertical leakage pathways, the two requirements for the development of drawdown dolines.

The influence of this mechanism on development of depressions in northern Guam is yet to be examined. There are several clusters of depressions on the northern Guam plateau found near its edge (above Haputo Beach, above Tarague Embayment, and in Pinate area and near the Hawaiian Rock Quarry in Mangilao) that I believe are most likely drawdown dolines. The sinkholes in Pinate are particularly impressive thanks to their close clustering and nearly identical shape and size. This conclusion is based on the following observations: the aforementioned dolines are funnel shaped, deep depressions (up to 30 meters), and small in area and circular in plan, with no point recharge. Some evidence of collapse was observed, but this should not be taken as evidence against drawdown origin as most drawdown dolines have an element of rock subsistence or settling in their development (Williams, 1985).

Nevertheless, collapse also should be considered as a potential origin of these depressions. They may be a result of collapse with subsequent breakdown of the sides and filling of the bottom, coming to mimic other non-collapse dolines. It is quite possible that a collapse feature is so completely mantled by soil and debris that it cannot be distinguished from dolines of other origins (White, 1988).

In any case, the dolines described here are true karst features. It is difficult to imagine depressions of such geometry being depositional in nature. Ponding Basin in Dededo

Tarague Copra Cave

Tarague Copra Cave is a single chambered cave breached by cliff retreat. It is located in the Tarague embayment and is entered by climbing the breakdown talus at the base of the cliff. The large entrance, almost 20 m by 6 m, is almost entirely blocked by large collapse boulders. The floor of the cave is comprised of soil and when I visited it, contained a large pile of coconut husks, probably accumulated there by coconut crabs (Birgus latro). The cave ceiling appears to be entirely a result of phreatic dissolution, with large cusps being the only visible feature. Cusps are thought to be phreatic dissolution features and their origin is discussed in detail in Frank et al. (1998). Virtually no vadose depositional features are present. The cave shows typical flank margin morphology, and early stages of development of secondary smaller rooms that end abruptly along with bedrock partitions, inland from the main chamber.

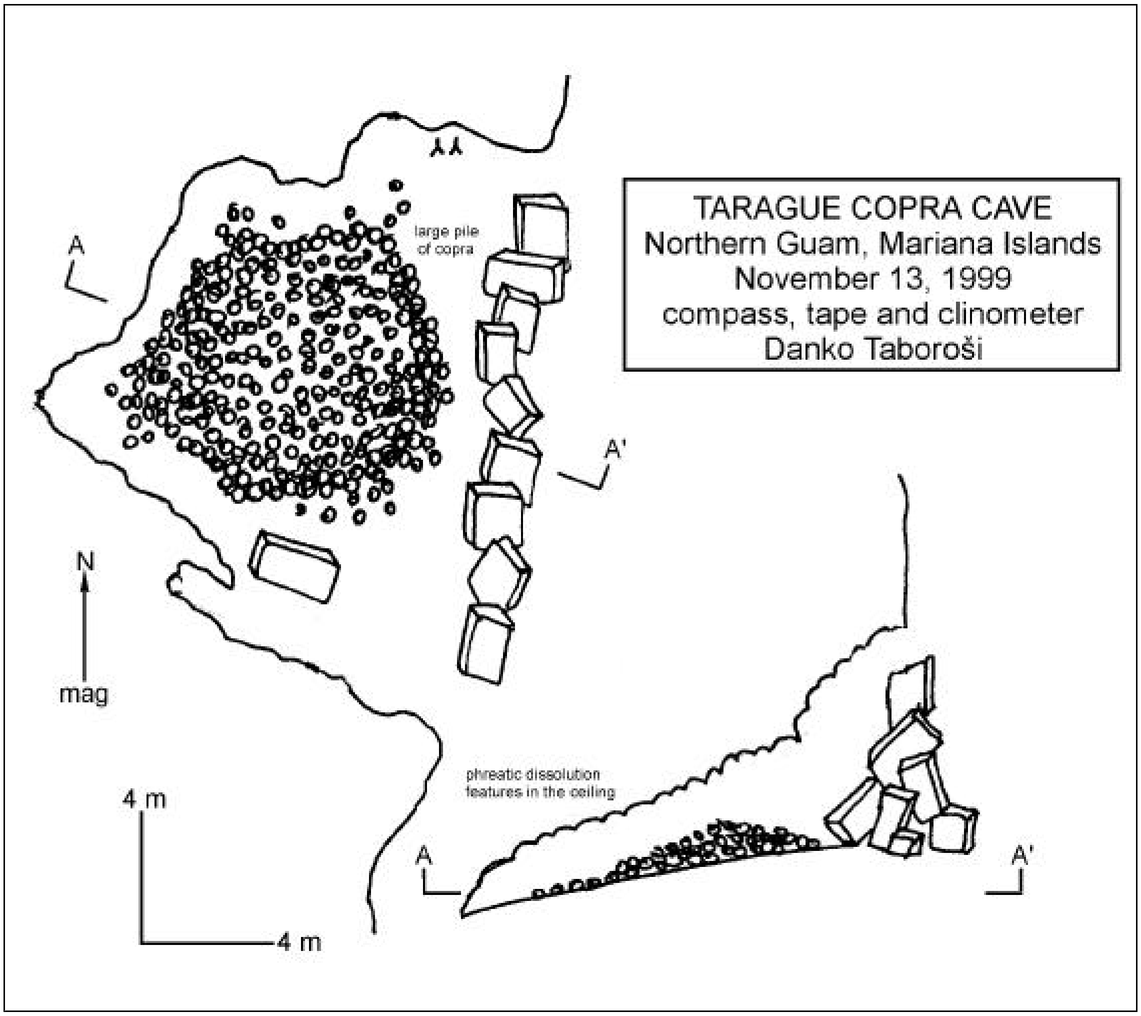

Figure 128: Map of Tarague Copra Cave

Tarague Well #1

A similar cenote is the nearby Tarague Well #1, which is about 5 meters deep to the top of the collapse rubble but provides access to a 10-meter deep water-filled cave. This cave contains submerged stalactites. Water is several meters deep but collapse rubble is extensive and blocks access to any potential passages.

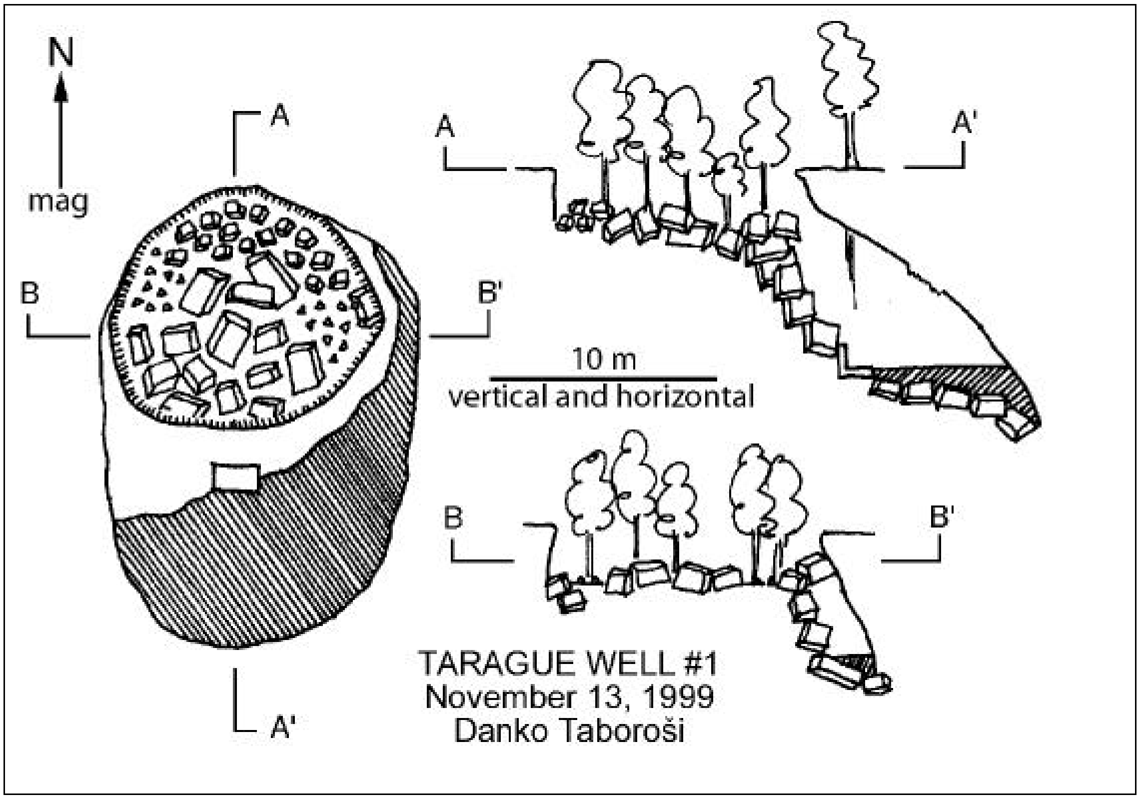

Figure 129: Map of Tarague Well #1

Tarague Well #2

Collapse in Tarague Well #2 was even more extensive, and access to freshwater in this vertical-walled cenote is limited to a very small pool in its southern end. This cenote contains several rusty 55-gallon drums. It appears to be fracture controlled, with a dissolutionaly enlarged fracture leading from the cenote's southern end. The fracture is filled with stalactites and flowstone.

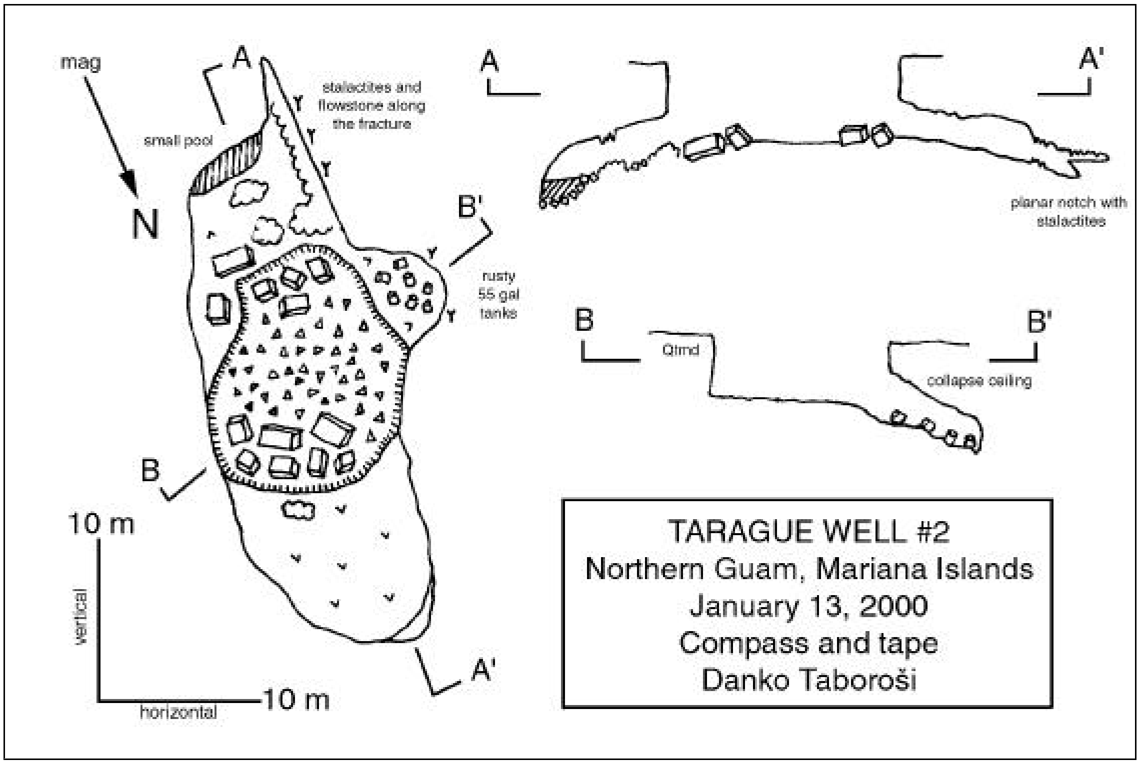

Figure 130: Map of Taraque Well #2

Taraque Well #3

Fourth in this series is Taraque Well #3, which undoubtedly looked like the other Taraque wells before, but extensive collapse has eliminated most of vertical walls and almost all access to freshwater. There is a shelter cave in its southwestern end (Plate 14, photo 5) with a very small pool. Most of the perimeter of this sinkhole is gently sloping, the floor is flat and filled with sediment and the cenote is difficult to recognize as a collapse feature.

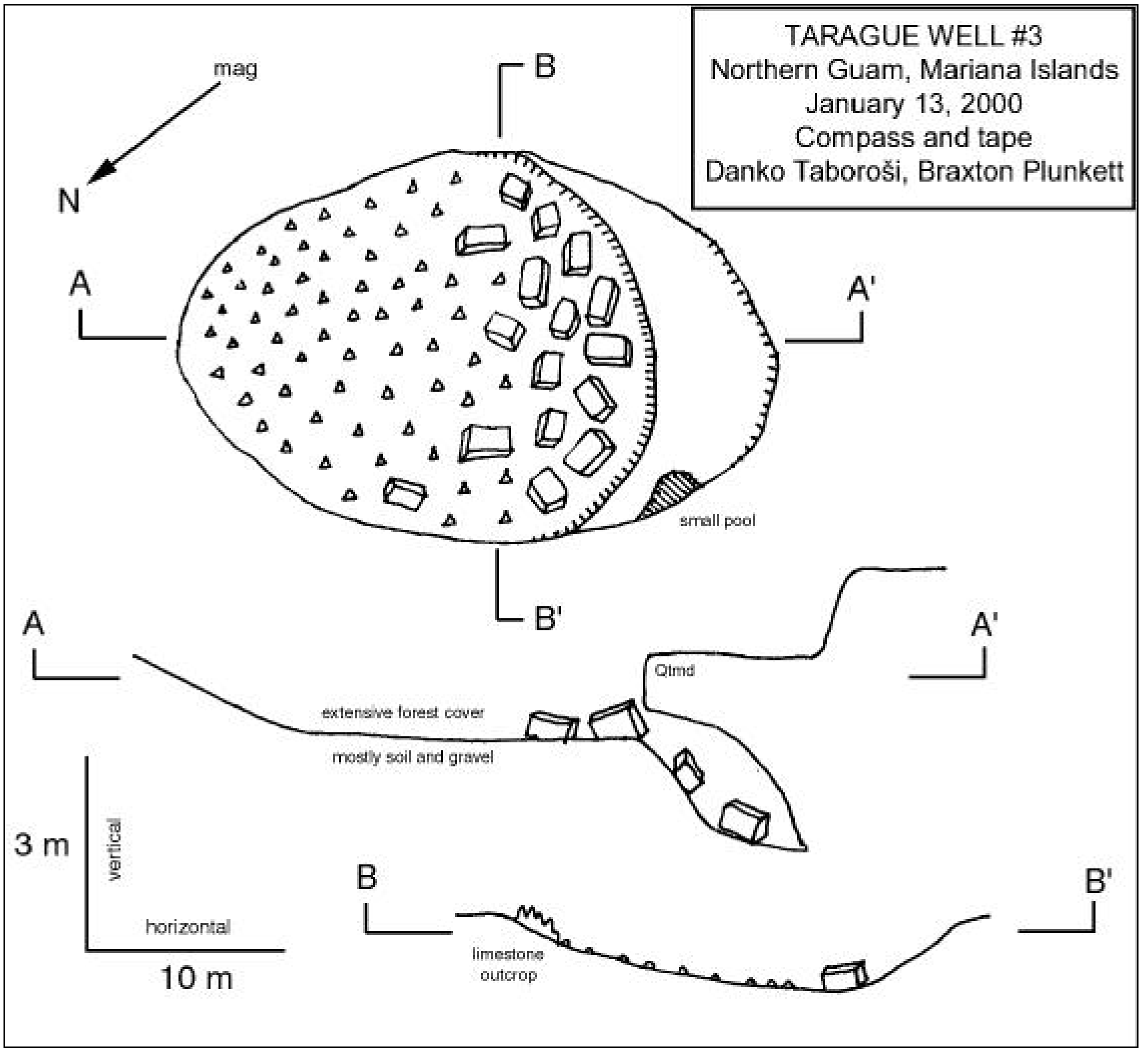

Figure 131: Map of Tarague Well #3

Tarague Well #4

All vertical-walled collapse cenotes on Guam are found within Tarague Embayment, on the north coast of Guam. The most similar to the classic model is Tarague Well #4. It is a vertical walled, 10-meters-deep collapse feature, filled with water in its southern end. The water-filled portion of the cenote was partially explored on SCUBA and contains a large collapse chamber reaching a depth of 15 meters. From this chamber, a narrow fracture allows access to the second chamber, reaching 21 meters in depth. The entire subaqueous portion of the cenote is characterized by collapse, with no depositional features in the ceiling and the entire floor being covered by collapse rubble. Collapse rubble shows extensive phreatic mixing zone dissolution, characterized by extremely jagged dissolution features. The ceiling is quite unstable and even disturbances from air bubbles hitting the ceiling during SCUBA diving cause a rain of limestone particles to fall through the water column. The underwater portion of the cenote was not explored in its entirety and there may be additional penetrable fractures. Navy divers who dove in this cave reported seeing a large cavern beyond the depth of 21 meters but did not explore it (Hogan, 1959).

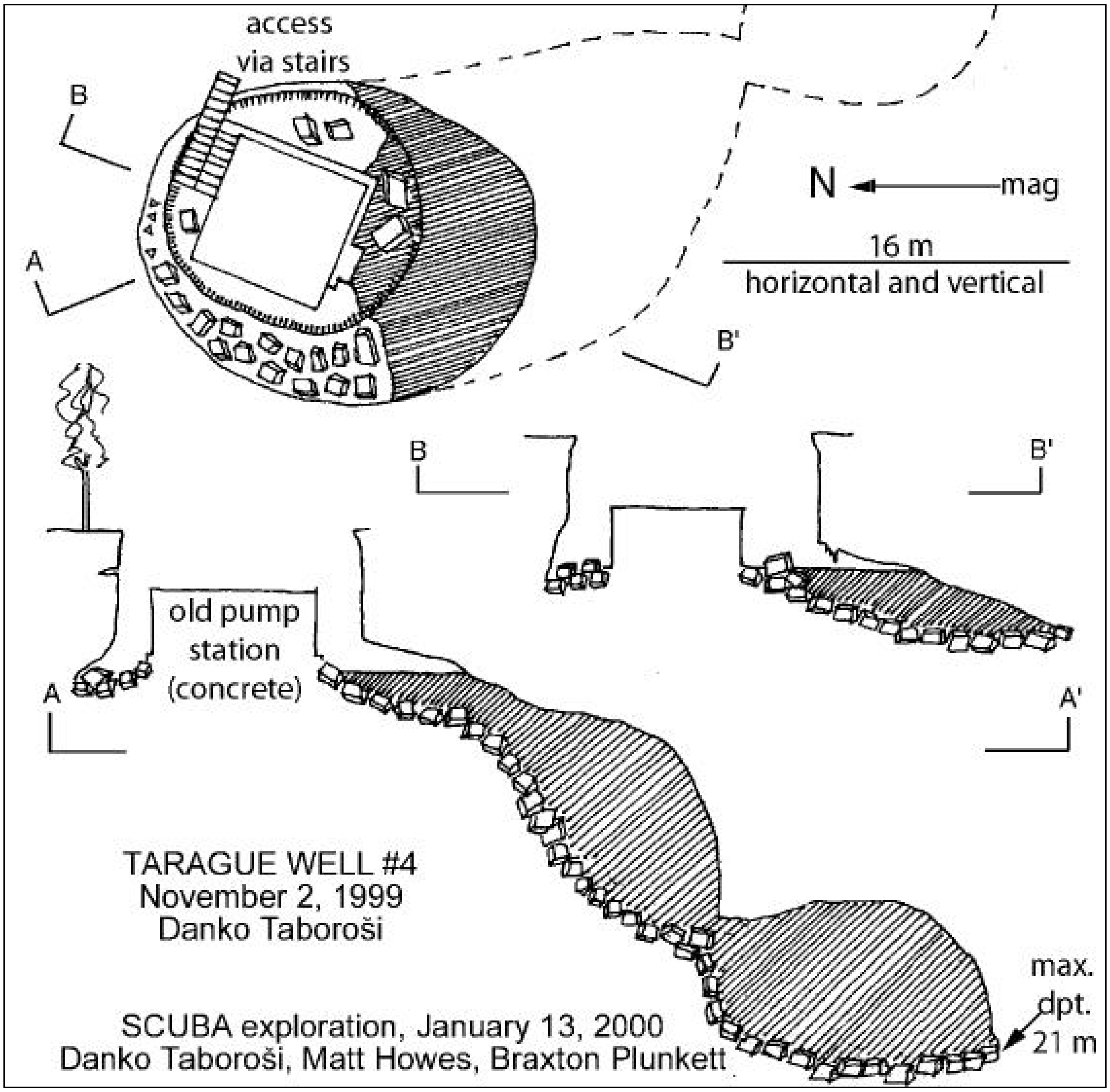

Figure 132: Map of Tarague Well #4

Tarague Well #6, #7, and #8

Three additional features known as Tarague Wells #6, #7 and #8 are reported to be collapse sinkholes with caves containing freshwater but could not be examined due to restricted access. Tarague Well #5 is different from the rest and is a small cave not associated with a sinkhole.

Yigo Sink

Allogenic point recharge sinks are not always located right on the contact. In one instance, there is evidence of water flowing over the limestone surface partially coated with alluvium, for up to 2 kilometers. This is the case of Yigo Sink, which does not appear to receive such allogenic input anymore, probably due to land development. However, its geometry and a trail of alluvium (mapped by Tracey et al., 1964) leading to the flanks of Mt. Santa Rosa make this is a typical allogenic point-recharge sink, although apparently inactive.

Discharge Features

Coconut Crab (Ayuyu) Cave

Some of the largest springs on the northwest coast of Guam are associated with coastal caves. The largest single point discharge feature identified so far in northern Guam is the Coconut Crab Cave. This cave is located about 300 meters south of Double Reef Beach. The entrance is at sea level, in a small cove containing several large boulders. A steady stream of freshwater emerges from the cave at the waterline, best seen at low tide. The cave has one large chamber, about 30 m by 20 m, no more than 4 meters tall. The room is partitioned by several flowstone divides, giving impression of passages. The floor is entirely made of flowstone or covered by coral rubble, with several scattered large collapse boulders and flowstone mounds. The back wall of the cave is made of large collapse boulders. The cave appears to extend further inland but is entirely filled by boulders and was not explored. Coconut Crab Cave was estimated to discharge 225 l/s (5 mgd) by Jocson (1998).

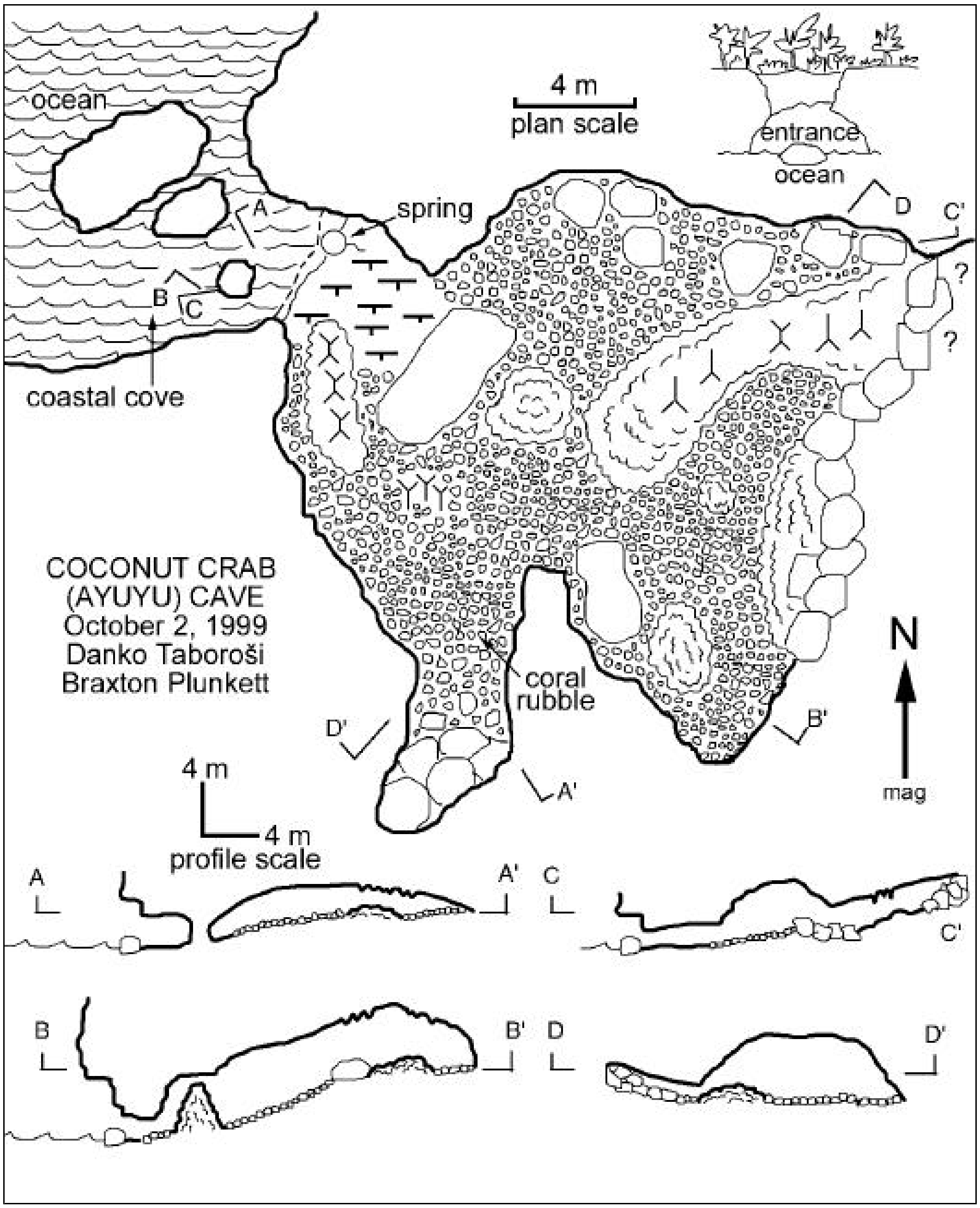

Figure 133: Map of Coconut Crab (Ayuyu) Cave

Janum Spring

Janum Spring—Water feeding this spring is probably allogenic water collected by the volcanic terrane at Mt. Santa Rosa. Basement conduits allow gravity-driven flow toward the coast, where the spring discharges from a cave, about 0.6 meters above mean sea level. The cave is a single passage more than 20 meters long, but its entrance was buried in the 1993 earthquake. Although shallow volcanic units probably provide basement for the conduits feeding this spring, no evidence of volcanic rock exists at the spring itself. A plume of sediment-laden water in the ocean adjacent to Janum Spring has been observed after a heavy rainfall episode (J. Jenson, pers. comm.).

Mataguac Spring Cave

Mataguac Spring Cave is located at the bottom of Mataguac Spring Sink, on the southeast flank of Mataguac Hill. It is a ponor of a small stream fed by Mataguac Spring and allogenic runoff from the local volcanic terrain. Runoff from Mataguac Hill and water from Mataguac Spring flow a short distance over the alluviated floor of the sink to the entrance of the cave, which is about 6 meters wide and 3.5 meters tall. The entrance leads to a single passage traversable for 15 meters. The floor of the cave is mud (from erosion of volcanic saprolite) and limestone rubble. This cave follows the contact between the Alutom Formation and overlying Mariana Limestone detrital facies, and is a vadose-cut canyon. However, volcanic bedrock and the geologic contact are not visible due to the extensive mud deposits.

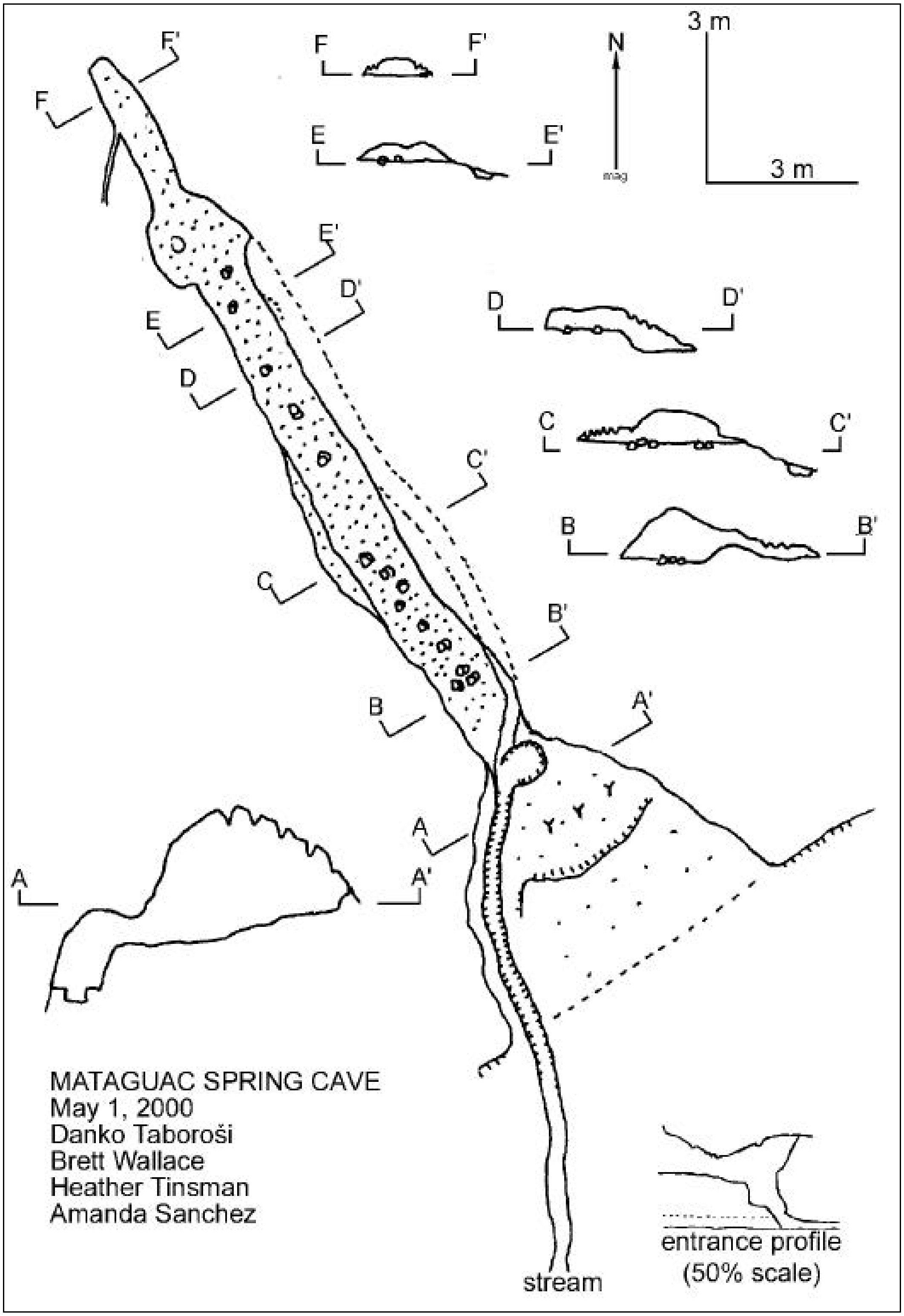

Figure 134: Map of Mataguac Spring Cave

Flank Margin Caves

Amantes Cliff Caves

A similar interpretation can be applied to massively decorated notches found on the cliffs at Amantes (Two Lovers) Point at four distinct horizons. The origin of these cave-like features on the outside of the cliff is debatable (flank margin caves vs. bioerosional notches). Several additional true caves are found in the Amantes cliffs and are probably flank margin. Several cave entrances are clearly visible in the cliff and have not yet been explored. Flank margin caves at different elevations appear to be breached and connected by vertical dissolution features (pit caves).

Castro's Cave

Another cave in a similar setting is nearby Castro’s Cave, located on the coastal terrace, at the base of a cliff, about 1100 meters southeast of Ritidian Cave and 2.3 km northwest of Mergagan Point, 400 meters inland from Castro’s Beach. It is entered through a very small opening (<1 m diameter) made by ceiling collapse. It contains one large, steeply sloping room, with the floor and ceiling subparallel. The room is heavily partitioned by extensive flowstone walls that give impression of several rooms and passages. The floor of the cave is made of flowstone and rubble; no bedrock can be seen. Rubble is dominant in the lowest portion of the cave where there is a freshwater pool (Plate 22, photo 7). Underwater observations of the pool revealed extensive rubble deposits and no submerged passages. This cave is extremely beautifully decorated, containing hundreds of massive stalactites, stalagmites and columns. Like in the nearby

Ritidian Cave, speleothems here are stained by black deposits, but to a lesser extent. The steep slope of this cave's floor is unusual for coastal water-table caves in Guam and is probably a result of collapse events.

Devil's Punchbowl

A unique collapse feature exists near the Hilton Hotel in Tamuning and is known as the Devil's Punchbowl. It is a dome shaped, single chambered room accessible though a collapse in the ceiling, but only by rappelling. This feature appears to intersect the freshwater lens in a shallow pool. The pool in the Devil's Punchbowl will be one of the Harmon Sink dye-tracing project monitoring locations (D. Moran, pers. comm.) There are no passages leading from the chamber. It appears to be a collapsed single-chambered phreatic void, possibly a flank margin cave.

Double Reef Arch

Double Reef Arch is a natural arch, probably formed by collapse of a discharging cave similar to nearby (not collapsed) Coconut Crab Cave. A coastal spring estimated to be discharging up to 7.5 million liters per day (Jocson et al., 1999) is located underneath the natural arch.

Fadian Fish Hatchery Cave

About 7.1 kilometers southwest of Marbo Cave is the very similar Fadian Fish Hatchery Cave. It was also opened by collapse at the base of a cliff and appears as a single chambered cave containing a large freshwater pool. With SCUBA, however, one additional submerged passage becomes accessible. It is a linear passage developed along a NW-SE trending fracture, visible in the ceiling, in the southwest part of the cave. This passage is vertically extensive at least to a depth of 8 meters below water level and is oriented toward the coast, 150 meters away. The lower parts of this passage are characterized by extremely jagged mixing zone dissolution features. No SCUBA investigation beyond this passage took place due to high risk of collapse and extreme clouding of water by easily disturbed silt deposits. The origin of silt (limestone derived or non-limestone) was not determined. Only Macrobrachium lar shrimp was found inhabiting this cave.

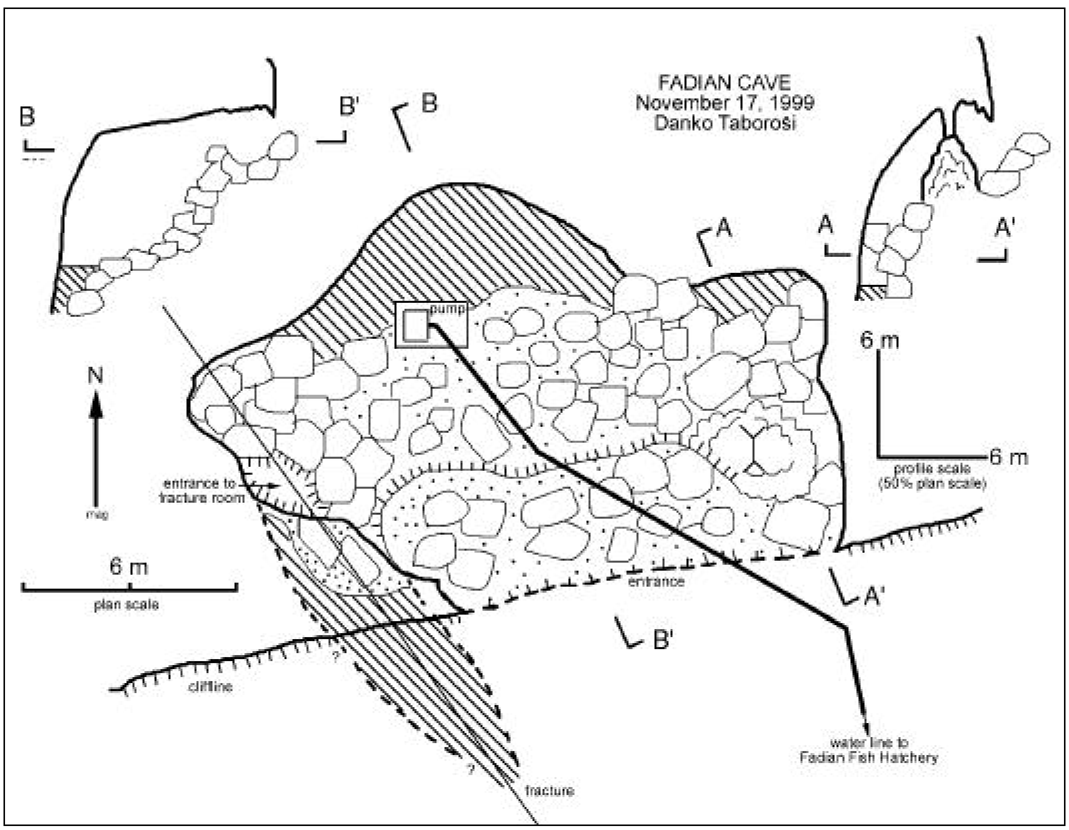

Figure 135: Map of Fadian Fish Hatchery (Fadian) Cave

Fafai Cave

Southward on the west coast, just north of Bijia Point is Fafai Cave. It is entered through an opening in the cliff about 6 meters above sea level, about 85 meters inland from the coast. It is a single-chambered cave with a pool of fresh water. The entire cave is floored by collapse blocks or sediment and flowstone deposited on top of the collapse blocks. Peripheral parts of the cave contain a freshwater pool. The extent of the cave under water is unknown but may be extensive as observed by snorkeling. Snorkeling among the large collapse blocks in the center of the room has revealed that they are extremely corroded by mixing zone dissolution, at the cave water level. As in the case of Frankie's Cave, it is possible that this cave is a part of a conduit that got elevated so that its flow was diverted to lower channels, as suggested by Lange and Barner (1995). A crab (Discoplax longipes) is common in this cave.

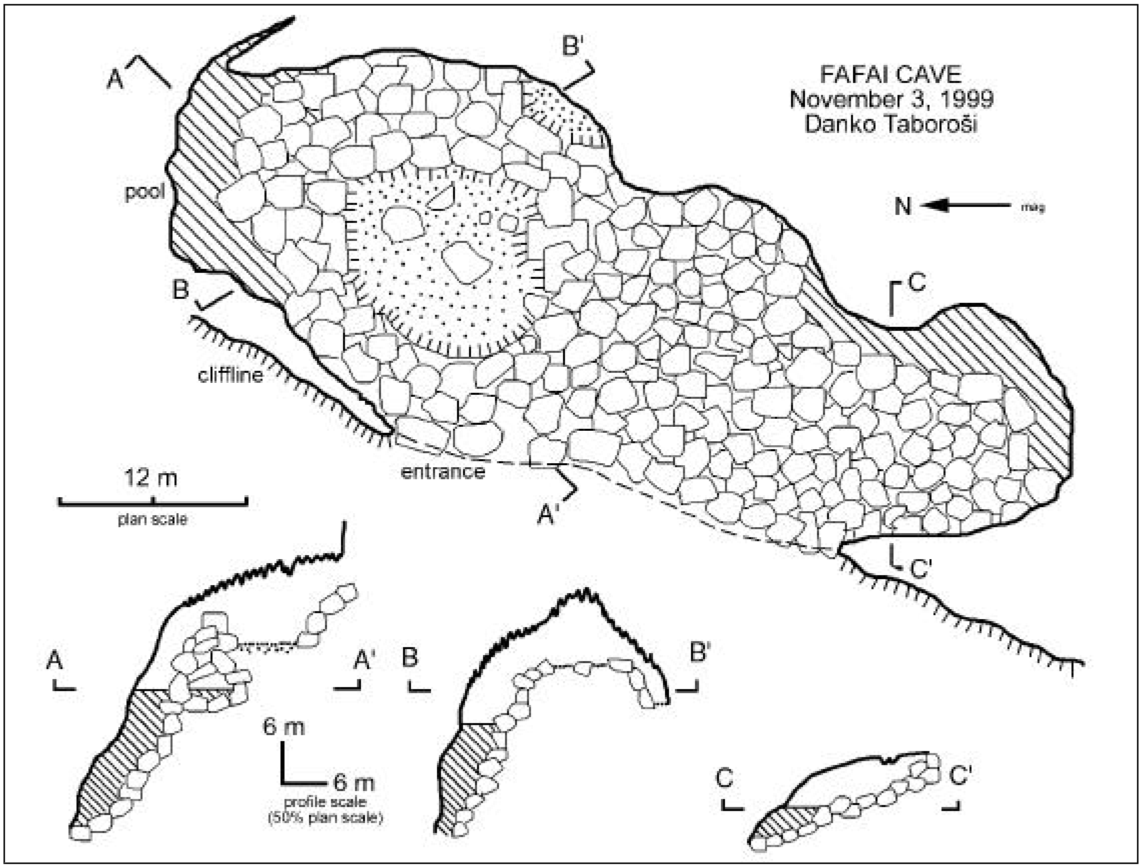

Figure 136: Map of Fafai Cave

Frankie's Cave

Frankie's Cave, located in the Double Reef area on the west coast of the island, is accessible through a collapsed ceiling. It is a single chambered cave with a fresh water pool, located 18 meters from the shoreline south of Double Reef Beach. Most of the cave's floor is covered by collapse rubble except for a single narrow subaerial passage leading from the main room, which seems to be floored by bedrock. The passage opens to a cliff overlooking the beach, about 5.6 m meters above the mean sea level. This passage may be a paleoconduit inactivated by relative sea level drop. In the submerged portions of the cave, existence of additional passages has been documented by snorkeling, but has not been further investigated using SCUBA due to difficulties of bringing equipment to this remote location. The coastline seaward of the cave forms a small cove with freshwater discharge estimated to be about 7.5 million liters per day (Jocson et al., 1999).

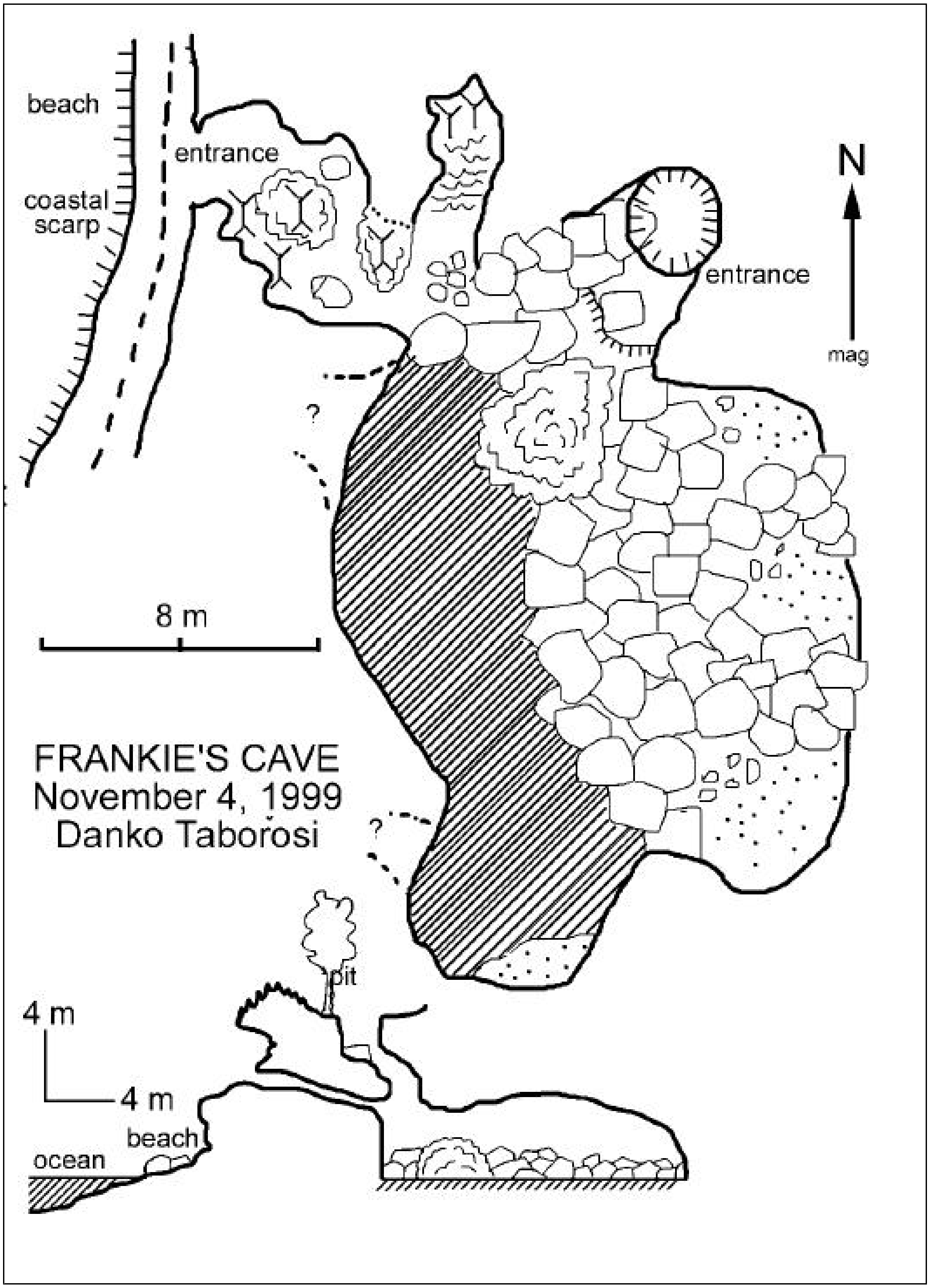

Figure 137: Map of Frankie's Cave

Pagat and Haya Pagat Caves

Pagat Cave, located on a sloping coastal bench on the east coast of Guam, about half way between Pagat and Campanaya points, 300 m inland from the coast. It is entered through a central collapse sinkhole, leading to two caves: Pagat Cave on the north side and Haya Pagat Cave on the south. The two caves were connected prior to collapse of the central sink. Pagat Cave entrance is about 4 meters wide and leads to a sloping passage containing extensive flowstone deposits and a large column. The passage widens to a narrow chamber containing a 0.5 m-deep freshwater pool, flowstone bank and several large stalagmites, and leads further north to the cave's only room. The room is about 15 m by 15 m, and its eastern half is entirely covered by a freshwater pool gradually deepening toward the north end and reaching a maximum depth of 3.5 m at the north wall. Narrow submerged passages lead from the north and east part of the water-filled room. They are not wide enough to accommodate a person. The pool's floor is mostly made of collapse rubble, partially cemented in places. Extensive submerged flowstone and partially submerged stalagmites are found in the southeast and north end of the pool. The eastern half of the room is covered by soil, sloping up toward the west, presumably derived from ceiling collapse. The cave ceiling shows excellent phreatic cusp development, indicating phreatic dissolution. Stalagmites have smooth surfaces and also show evidence of dissolution under phreatic conditions, which is expected given dynamic sea level changes experienced by Guam. Shrimp (Macrobrachium lar and Atyoida sp.) were found in the cave's pool.

Haya Pagat Cave entrance is 10 meters south of Pagat Cave entrance, on the south end of the central collapse sink. It contains a single chamber, approximately the size of Pagat Cave's only room, covered by soil and collapse rubble. The south wall of the room is an extensive flowstone partition that can be negotiated in several high places to reach the back of the room. The deepest portion of the room, behind the flowstone partition, reaches freshwater at the same level as Pagat Cave's pool. Water in Haya Pagat Cave, however, does not form a pool and is barely visible among rubble blocks.

Pagat and Haya Pagat Caves fit the flank margin model for cave development (Mylroie and Carew, 1990) but differs from most of Guam's other flank margin caves or coastal freshwater caves in the significant respect that it is one of only three water table caves (Castro's, Joan's and Pagat) where no additional submerged passages could be identified by snorkeling. A map of Pagat and Haya Pagat caves was prepared by Mylroie et al. (submitted).

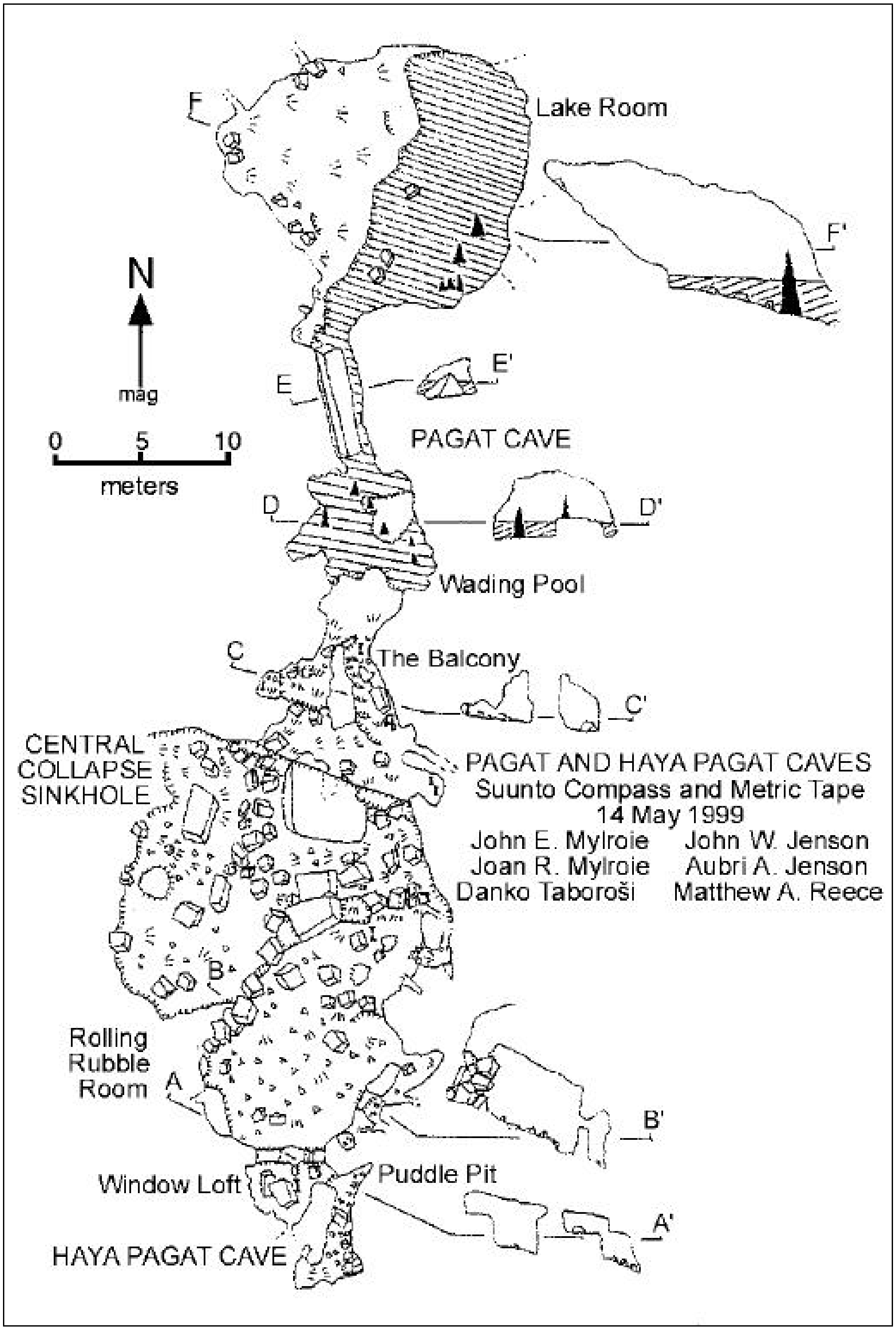

Figure 138: Map of Pagat and Haya Pagat Caves

Joan's Cave

Joan's Cave (Hilaan Natural Well #1) is located at the foot of the cliff about 130 meters north from the Lost Pond, in Hilaan area on the Philippine Sea. The cave is entered through a small collapse in the ceiling, and leads down about 12 meters to the freshwater level. The floor of the cave is mostly comprised of collapse rubble with some flowstone deposits. This cave is in latter stages of collapse, with the heavily fractured ceiling still containing few insitu stalactites. The cave is a series of irregularly shaped small rooms at several levels. Several passages are obstructed by collapsed boulders. There are four freshwater pools in the lowest room, two of which are about 2 m deep and the other two less than 0.5 meters deep. No traversable submerged passages were identified by snorkeling.

Joe Quitigua's Water Cave

Joe Quitigua's Water Cave is another example of a collapsed cave, acting as a shallow phreatic conduit. It has no above-water component and from the outside appears as a small shallow perched water pond, breached by excavation in the Hawaiian Rock quarry in Mangilao. At the northwest edge of the pond, a small hole about 0.5 m in diameter leads to an entirely water-filled room, without any air pockets. The room appears to be oriented along a fracture, easily visible in the ceiling. A single stalactite and some flowstone deposits can be seen but most of the walls, floor, and ceiling of this chamber are a result of collapse. SCUBA exploration of this cave was attempted but aborted because exhaled air bubbles disturbed the ceiling and caused a "rain" of limestone chips in the water column. A fracture of NWSE orientation is visible in the cave's ceiling. Its northwest end points inland, towards the cliffs and an unusual large tube-like cave (Hawaiian Rock Quarry Cave) and the southeast end towards the ocean and a small bay with documented freshwater discharge (Hawaiian Rock Quarry Beach Springs). The Hawaiian Rock Quarry Tube Cave has developed in poorly cemented coarse rubble facies and shows no depositional or dissolutional features. The orientation of the cave is perpendicular to the modern coastline. The cave's location and orientation suggest that it may have developed as a preferential flow path to the coastline and may be an abandoned part of the system now containing Joe Quitigua's Water Cave and Hawaiian Rock Quarry Beach Springs, but this is only speculative. This pond and cave is inhabited by Macrobrachium lar shrimp and an endemic Orcovita mollitia crab (G. Paulay, pers. comm.)

Lafac Grotto

Another impressive collapsed phreatic chamber is the Lafac Grotto. This massive void was breached by roof collapse and, in two additional places, by wave erosion and cliff retreat. It contains two natural arches and possibly several short cave passages. It is quite similar to The Grotto on Saipan. Connections to the ocean in Saipan's Grotto are submarine, and in Lafac Grotto above the sea level.

Marbo Cave

Marbo Cave, also known as Campanaya Cave or Campanaya Spring, is a popular picnic spot, located at the base of a cliff on the north end of Sasajyan embayment. This cave was used as a water source by the Japanese Military forces from about 1942 to 1944 and by the U.S. Army from 1947 to 1950 (Randal and Holloman, 1974). A large collapse entrance at the base of a cliff leads into cave's only subaerially exposed room. The room is some 20 meters across and contains a freshwater pool. The entire floor of the cave is covered by collapse rubble. No bedrock floors are visible. A small part of the cave floor, adjacent to the entrance, is taken up by a concrete platform. A large collapse boulder to the left of the platform separates the cave into two portions. The part between the boulder and the platform (shallow pool) is up to 2 meters deep, while the part on the far side of the boulder (deep pool) is about 6 meters deep. Few calcite depositional features, no phreatic dissolution features and extensive algal (purple) coating are visible in the subaerially exposed walls of the cave. Prior studies have described this cave as a single chamber containing a freshwater pool and no evident outlet (Lange and Barner, 1995). However, SCUBA investigation of this cave revealed additional rooms and passages. An 8 m long tubular passage, elliptical in cross-section, starts at the bottom of the deep pool in the west portion of the cave and extends upwards at a ~45o angle. The passage terminates above the water level and contains a small air pocket, penetrated by plant roots. The walls and ceiling of the air pocket are made of soil, not limestone. Also at the bottom of the deep pool, another narrow passage leads to a small room containing hundreds of small stalactites, now completely flooded at a depth of about 4 meters. Salinity in the deep pool was measured to be 1.9 ppt at the surface and 2.6 ppt at a depth of 6 m. The temperature was uniform, at 26.2oC (08/11/1999).

The most extensive passages start from the shallow pool end, at the southeast end of the main room. A nearly vertical flooded passage leads into a large room, some 20 meters across. Its floor is at a depth of about 7 m and is covered by collapse blocks; room walls are made of bedrock. Additional narrow passages extend deeper. A few calcite deposition features (mostly broken flowstone fragments and several isolated in-situ stalactite deposits) are visible, especially just below the cave water level. Deeper passages are all made by collapse rubble and boulders and contain some silt and clay deposits. The collapse boulders show extremely jagged mixing zone dissolution features. Some of these passages appear large enough for a diver to pass but were not further investigated due to high risks of collapse and disorientation.

Rogers and Legge (1992) write that a stream with a discharge of approximately 113,600 liters per day traverses the freshwater pool from west to east, but it is unclear how this was measured or observed. No movement of water is detectable by casual observation. However, indirect evidence for conduit flow in this cave is based on the cave's fauna and geophysical investigations.

Adult Eleotris fusca fish and Macrobrachium lar shrimp were recorded in the cave on several occasions. These organisms are amphidromous, meaning that their reproductive cycle involves a marine larval stage. Larvae complete their development in the ocean and migrate back into freshwater (cave) habitat to mature and reproduce (B.

Tibbatts, pers. comm). Therefore, for amphidromous species to inhabit a cave, there have to be direct connections between the cave and the ocean large enough for larvae to swim through. Larvae of Eleotris fusca are about 18-22 mm long during recruitment; shrimp larvae are about 4-5 mm long (B. Tibbatts, pers. comm).

A study by Lange and Barner (1995) found a significant natural potential anomaly immediately seaward from the cave leading them to conclude that the anomaly overlies “the conduit carrying water from the cave system toward the sea,” based on their assertion that the natural potential method is the only geophysical technique that responds to the movement of fluids, rather than their mere presence (Lange and Barner, 1995).

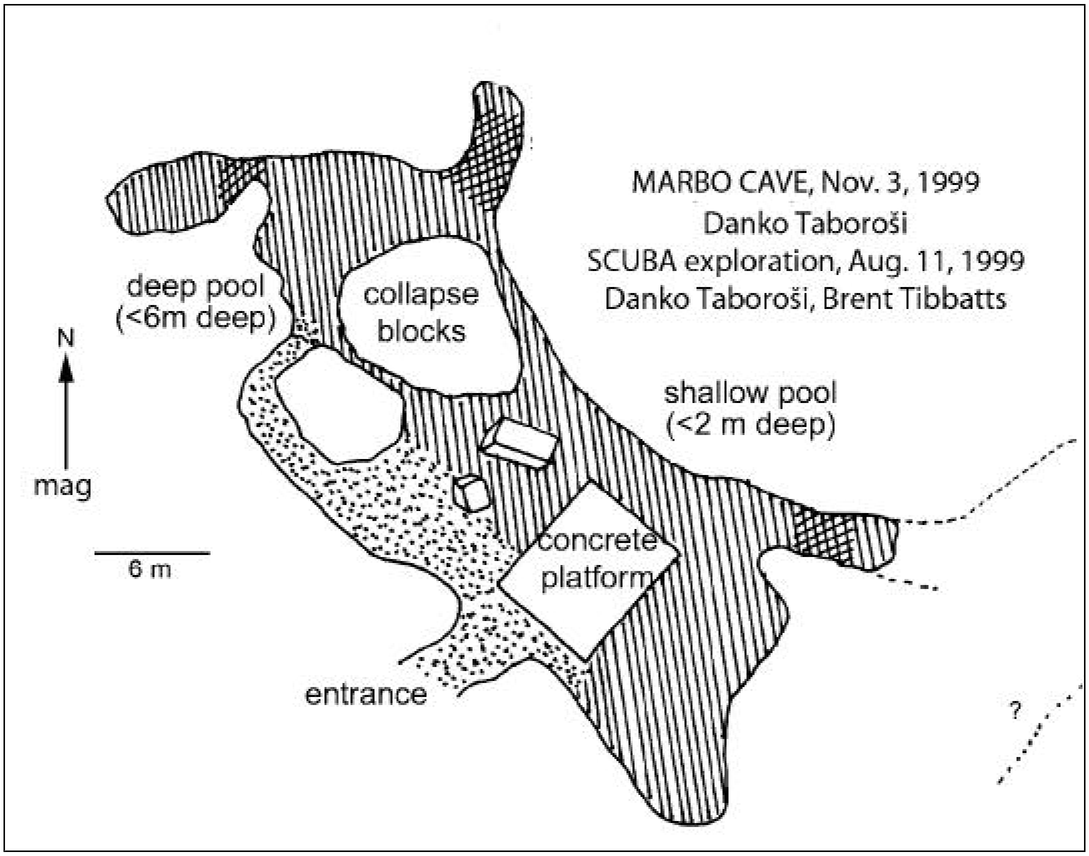

Figure 139: Map of Marbo Cave

Matt's (Matt’s Freshwater) Cave

Additional submarine vents along the northwest coast were located during this project, the deepest and largest being Matt’s Freshwater Cave. This cave discharges a significant amount of freshwater but the discharge volume is difficult to estimate. Located at a depth of 11 meters, the cave has a single oval chamber, extending into the cliff. Freshwater discharges from several points in the cave, all dissolutionally enlarged fractures, about 10 cm wide. In addition to submarine discharging caves, there are also submerged fractures similar to No Can Fractures that discharge freshwater.

Ritidian Beach Caves

Ritidian Beach Cliffline is perhaps the most accessible place to observe extensive flank margin caves that appear to have been breached by cliff retreat. This low cliff is located between Ritidian access road and Ritidian beach and is subparallel to the beach (see location map inset). After a surface survey of more than 400 meters of this cliffline, five caves and extensive cave features on the outside cliff walls were identified. Going from northeast to southwest along the cliffline, the first cave encountered is the Ritidian Beach Cave. It is a flank margin cave, single chambered and elongate in shape, apparently developed along a fracture visible in the ceiling. Most of the cave is undecorated with few stalactites and vadose fluting in the walls. The southwest part of the room, however, is separated from the rest of the cave by several column partitions; this part is well decorated and contains numerous cusps in the ceiling, and dissolved speleothems. A smoothly dissolved stalagmite and a sharply dissected stalagmite cut by phreatic dissolution are striking features, indicating a relative sea level rise and submergence of vadose features into the phreatic zone. Evidence of phreatic dissolution on vadose features in flank margin caves implies the following sequence of events:

1) formation of large cavities by the dissolution in the mixing zone

2) relative drop of sea level and placement of caves in the vadose zone where speleothems could be deposited

3) relative rise of sea level and re-placement of caves in the phreatic zone where dissolution of speleothems took place

4) relative drop of sea level and another vadose episode

The actual number of sea level changes and vadose and phreatic episodes at any given site is impossible to evaluate, since evidence from previous episodes is obliterated by the most recent one.

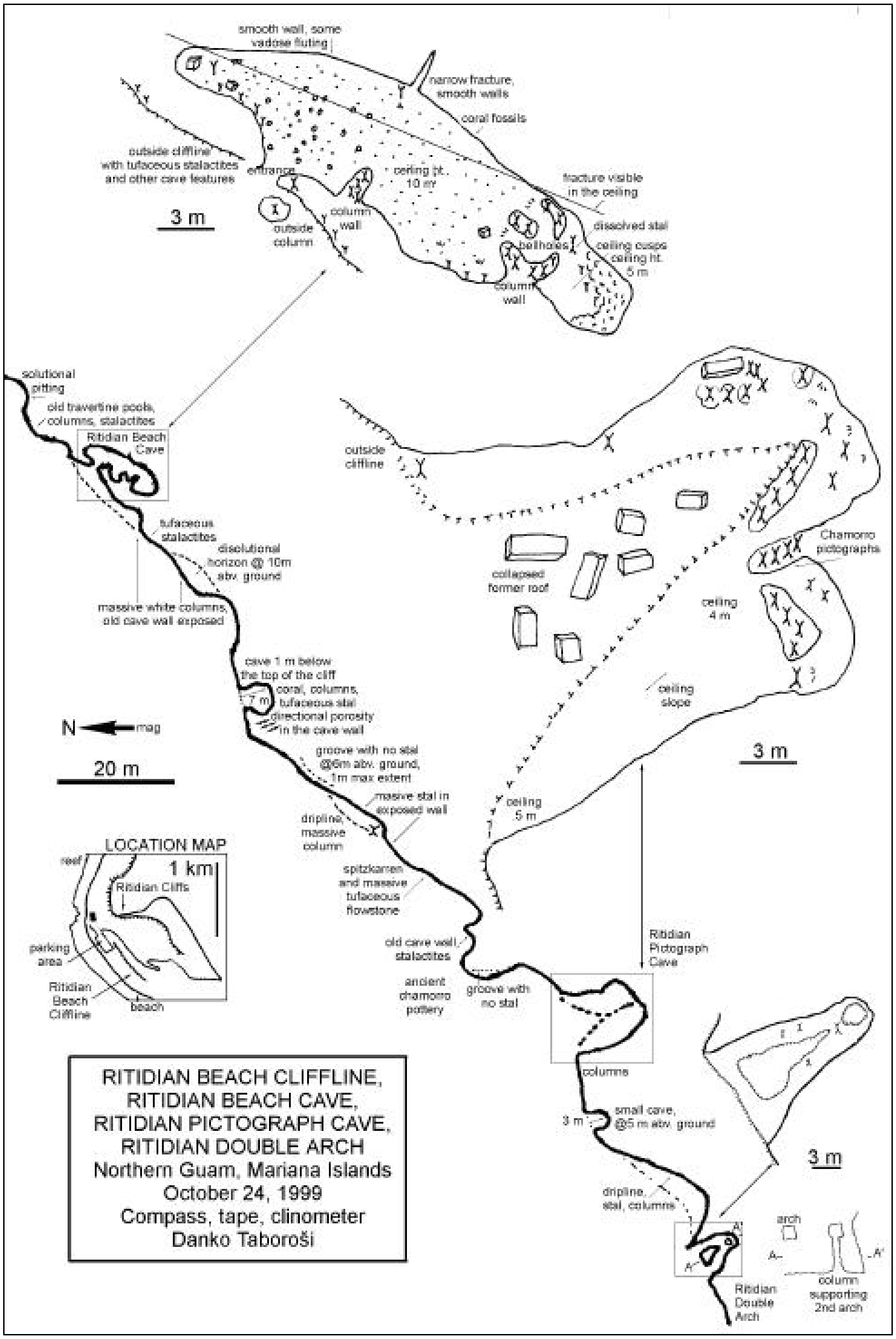

Figure 140: Map of Ritidian Beach Cliffline, Ritidian Beach Cave, Ritidian Pictograph Cave, and Ritidian Double Arch

Ritidian Cave

Probably the largest flank margin cave on Guam is Ritidian Cave, located on the coastal terrace about 950 m east-southeast of Ritidian Point, at the base of a cliff 360 meters away from the coast in Guam National Wildlife Refuge. It is entered through a very small opening (1 m diameter) made by ceiling collapse. The antechamber of the cave, separated from the main room by a massive flowstone partition, is steeply sloping, with a decorated ceiling subparallel to the floor. The floor is made of flowstone, partially covered by collapse rubble and soil. The massive flowstone partition can be negotiated in one place to enter the cave's large room. This room is circular in plan (~36 m across), with a high (10 m), flat ceiling. The ceiling is relatively undecorated suggesting frequent breakdown. It is also heavily fractured, and massive stalactites have developed along some of the fractures. The floor, however, shows few collapse features. The central part of the room contains a large collapse block. Most other collapse blocks have been cemented by flowstone, visible in the peripheral parts of the room. The distal end of the room contains a freshwater pool, with collapse rubble floor and extensive submerged vadose deposition features. Submerged passages can be seen by snorkeling in the pool but cannot be explored without SCUBA. The most impressive features about this cave are its spacious main room and numerous massive stalagmites. Most speleothems, however, are covered by black material. Speleothems are white underneath the thin black layer, suggesting that the deposition of this layer was a recent event. The cave's ceiling appears to be quite thin, with plant roots penetrating it in places, and it is possible that the black coating of the cave may be from organic material transported from the epikarst above, although this is only a speculation, as I had no time for detailed investigation of its origin.

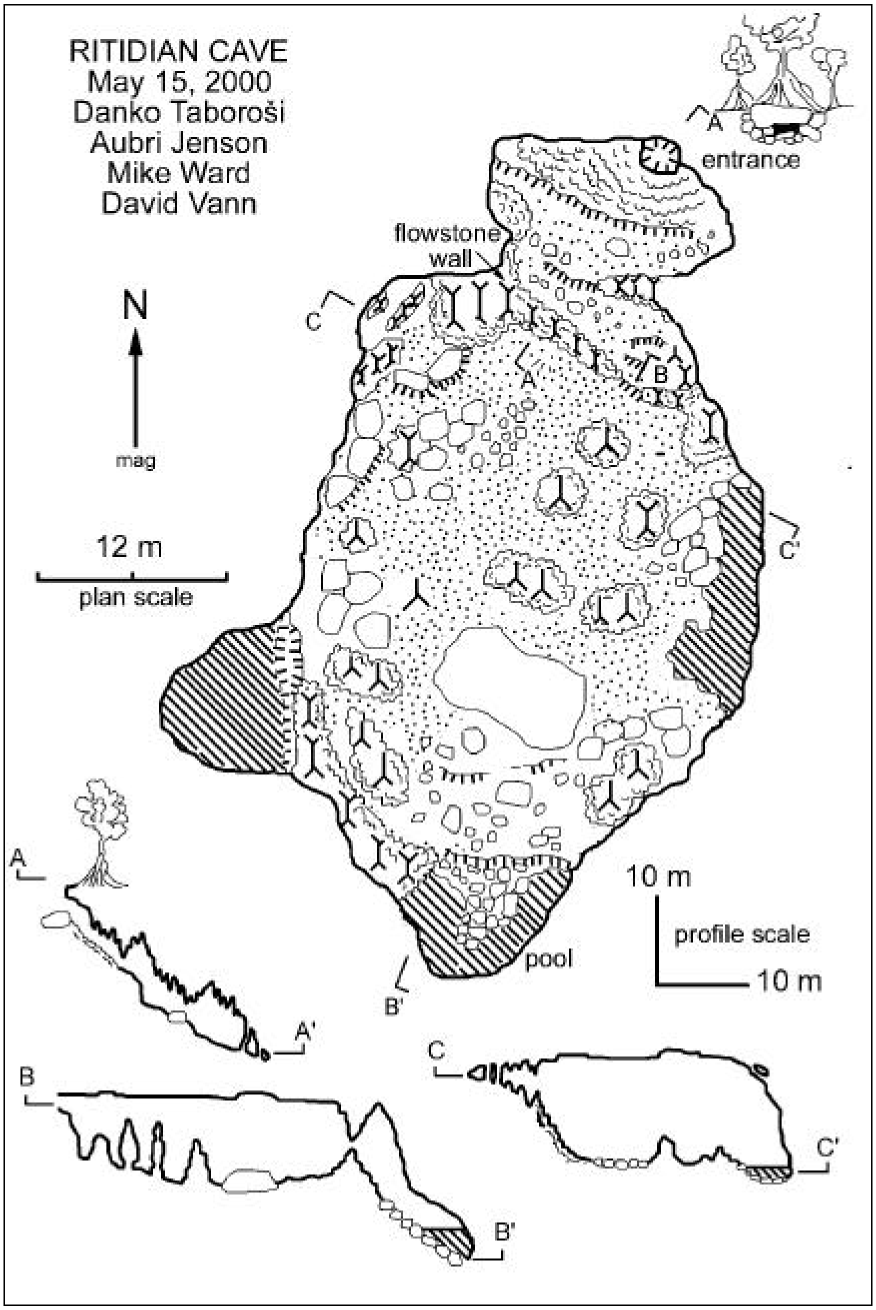

Figure 141: Map of Ritidian Cave

Ritidian View Cave

Ritidian View Cave is similar to the Tarague Beach View Cave. It is entered via a cliff-side entrance, nearly 20 meters wide and 8 m tall, located about 10 meters up a cliff overlooking Ritidian Beach (Ritidian Cliff). The large entrance and massive stalactites are visible from the beach and especially the Ritidian access road. The cave has one large room, divided into several sections by column partitions. Most of the speleothems are grotesquely sculptured by phreatic dissolution. The back part of the cave has a black soil-infilled pit, about 2 meters deep. Another large cave is located at the base of the cliff, on the right-hand side of the road just by the gate at Ritidian Wildlife Refugee.

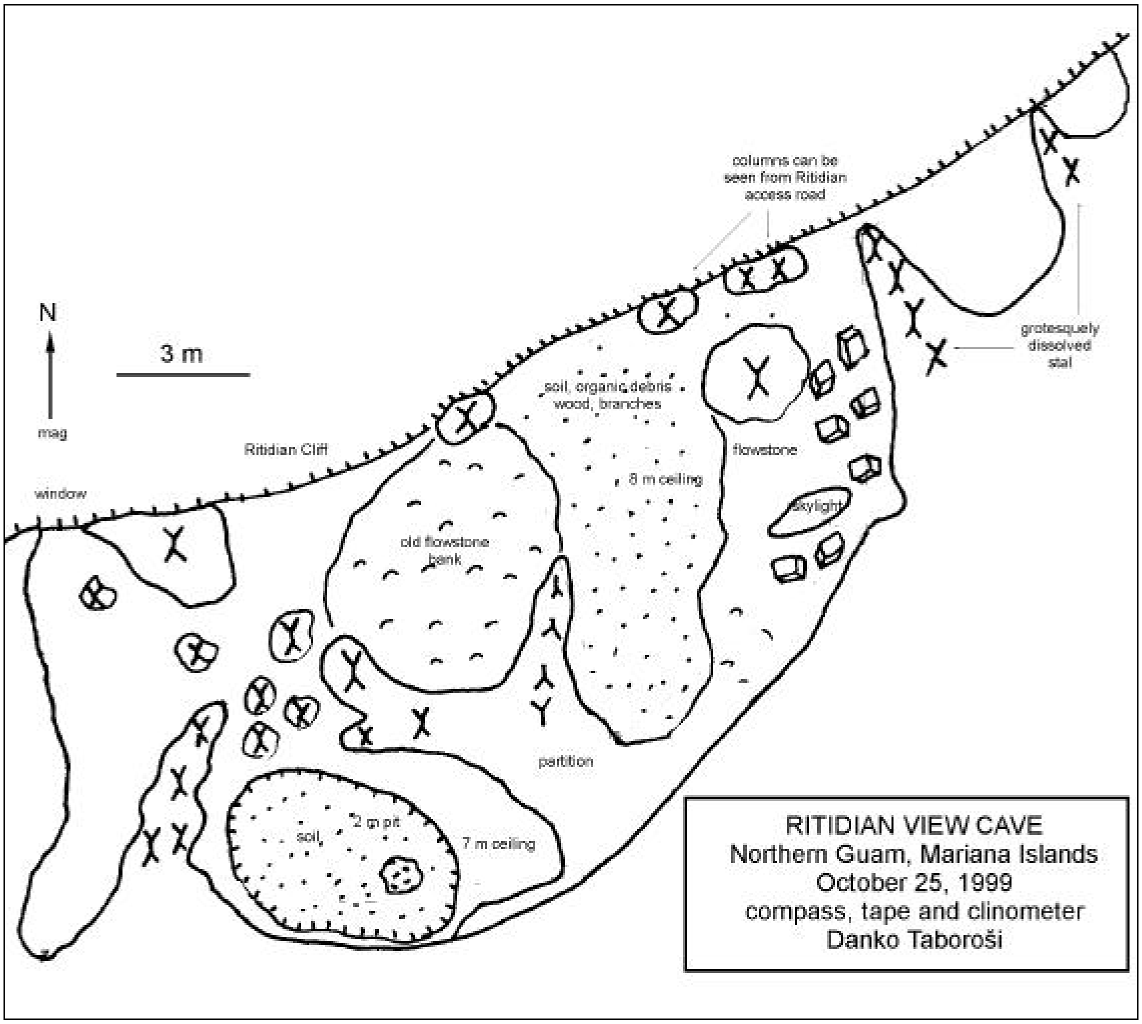

Figure 142: Map of Ritidian View Cave

Tarague Beach View Cave

Tarague Beach View Cave is more typical of Guam's flank margin caves with cliff-side entrances. The entrance is located about 15 meters up the coastal cliff, just west of Mergagan Point, where a large tension dome remains of another flank margin cave (Mergagan Point Cave), collapsed in a recent earthquake. Tarague Beach View Cave has one long room, about 16 m by 2-6 m, nearly partitioned into two by a group of large columns. The cave exhibits massive stalactite and column development, many of which have been grotesquely dissolved by subsequent phreatic dissolution. Dissolutional sculpturing of speleothems is reminiscent of that in the flank margin caves of Isla de Mona, Puerto Rico. The ceiling and walls show phreatic cusp development, which has been overprinted in the back portion of the cave by vertical vadose fluting. Vadose input is evident in the back portion, from numerous small stalactites and soda straws in the ceiling, dripstone on the floor, along with thick organic soil deposits, which have probably been brought by vadose water through the epikarst. The cliffline walls outside of the cave show phreatic cusp development, indicating that cave development was much more extensive before destruction by cliff retreat. Horizontal notches showing beads-on-a-string morphology (Vogel et al., 1990) and massive grotesquely dissolved speleothems extend along the cliff at the level of the cave entrance and another level some 15 m above (Taborosi, 2000)

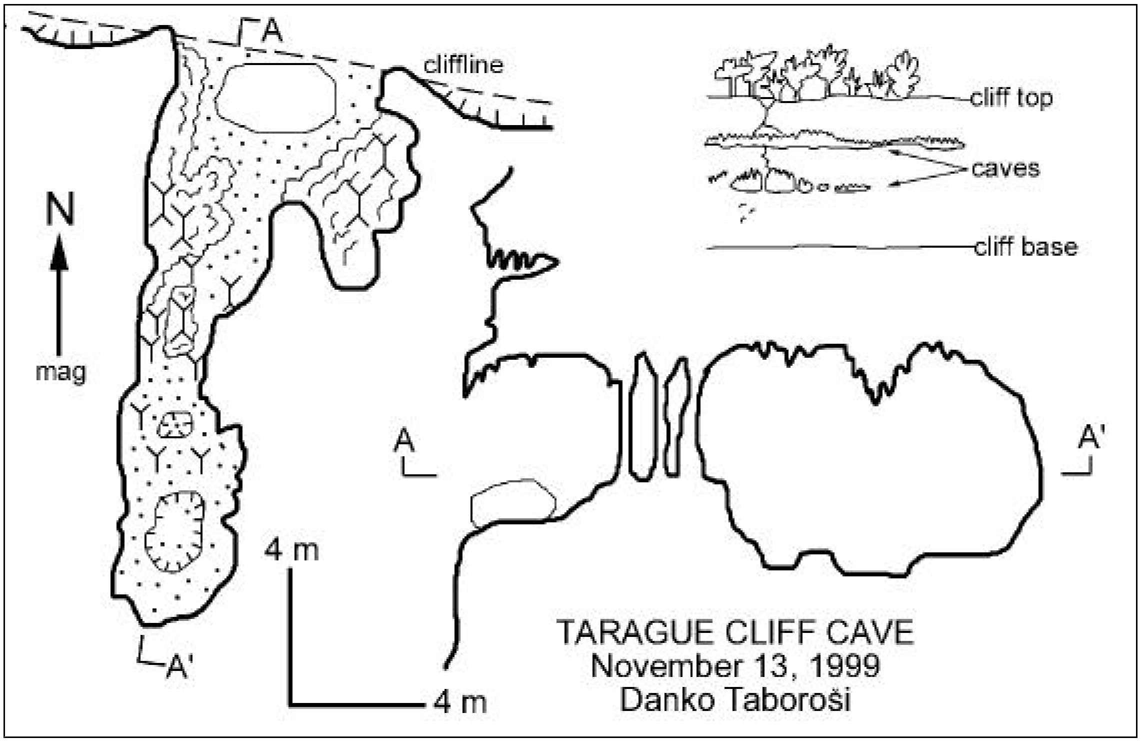

Figure 143: Map of Tarague Beach View (Tarague Cliff) Cave

Tarague Well #5

Another freshwater cave, Tarague Well #5, has a similar entrance and could be a flank margin cave breached by ceiling collapse. Located just 70 m inland from Tarague Beach, it is almost entirely flooded. A narrow, steeply inclined, soil-floored tube leads to the freshwater level, exposed as a small pool, less than 1 m in diameter. Sub-aqueous extent of the cave is unknown.

Mixing-Zone Fracture Caves

Menpachi Fracture

Menpachi Fracture is located about 100 meters north of the north end of Double Reef Beach. It is the widest discharging fracture identified so far. The mouth of the fracture is about 5 meters wide and interrupts the coastal algal reef terrace. It is not clear whether freshwater discharge dissolved the coastal terrace away or prevented its growth. Orientation of the fracture is normal to the coastline, east-northeast. The first 25 meters from the mouth appear as a canyon, having no roof and discharging a steady stream of water. After the 25 meters, fracture abruptly narrows and closes about 5 meters above the waterline. It is traversable for another 15 meters beyond that point, after which is becomes too narrow. In the un-roofed portion of the fracture the bottom is covered by carbonate sand deposits. In the final 15 meters, bottom of the fracture is limestone bedrock, without any sediment. Menpachi fracture receives flow from two large and one small tributary fracture, and shows evidence of another, now abandoned tributary. Estimated discharge from this fracture is 40 l/s (0.9 mgd) (Jocson, 1998).

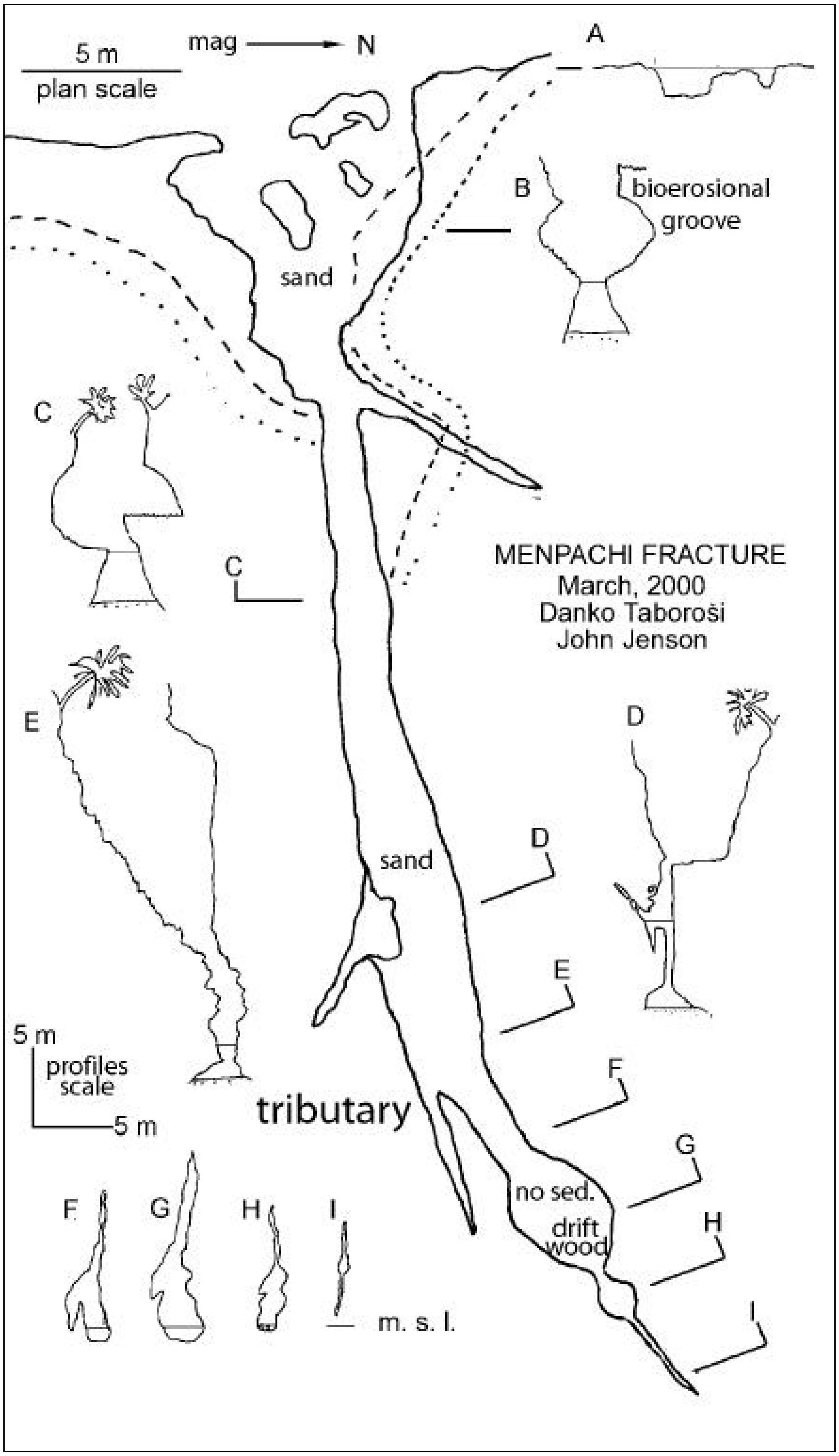

Figure 144: Map of Menpachi Fracture

No Can Fracture

No Can Fracture is located about 650 meters north of Double Reef Beach. Oriented normal to the coastline, it extends east into the coastal cliff. It is 0.5 meters wide at its entrance in the coastal cliff. Seaward of the entrance, the fracture forms a 3-m wide disruption in the coastal algal reef bench. By immersing oneself in the water flowing through the fracture, it is possible to swim through the 0.5-wide opening in the coastal cliff into the fracture that, after 2.5 meters, widens to 1.5 meters. The fracture then narrows to about a meter wide, before it widens again to form a small chamber almost 3 meters wide. The fracture then narrows to less than a meter wide before reaching the final wide chamber, about 2 meters wide. At this point, the floor of the fracture emerges above sea level and the fracture can be further traversed by walking instead of swimming. Only 5 meters further, 35 meters from the entrance, the fracture becomes too tight to traverse. The back end of the fracture contains partially cemented reef debris and organic debris, pushed there by storm waves. Most of the fracture floor, however, is limestone bedrock, lacking sediment. The fracture is vertically extensive but closes at 8-9 meters above waterline. Organic debris, such as driftwood and coconuts, are often found wedged in the narrow upper parts of the fracture, a result of storm waves. Discharge is estimated to be 18 l/s (0.4 mgd) (Jocson, 1998). Two small fractures in the walls of No Can appear to be tributaries.

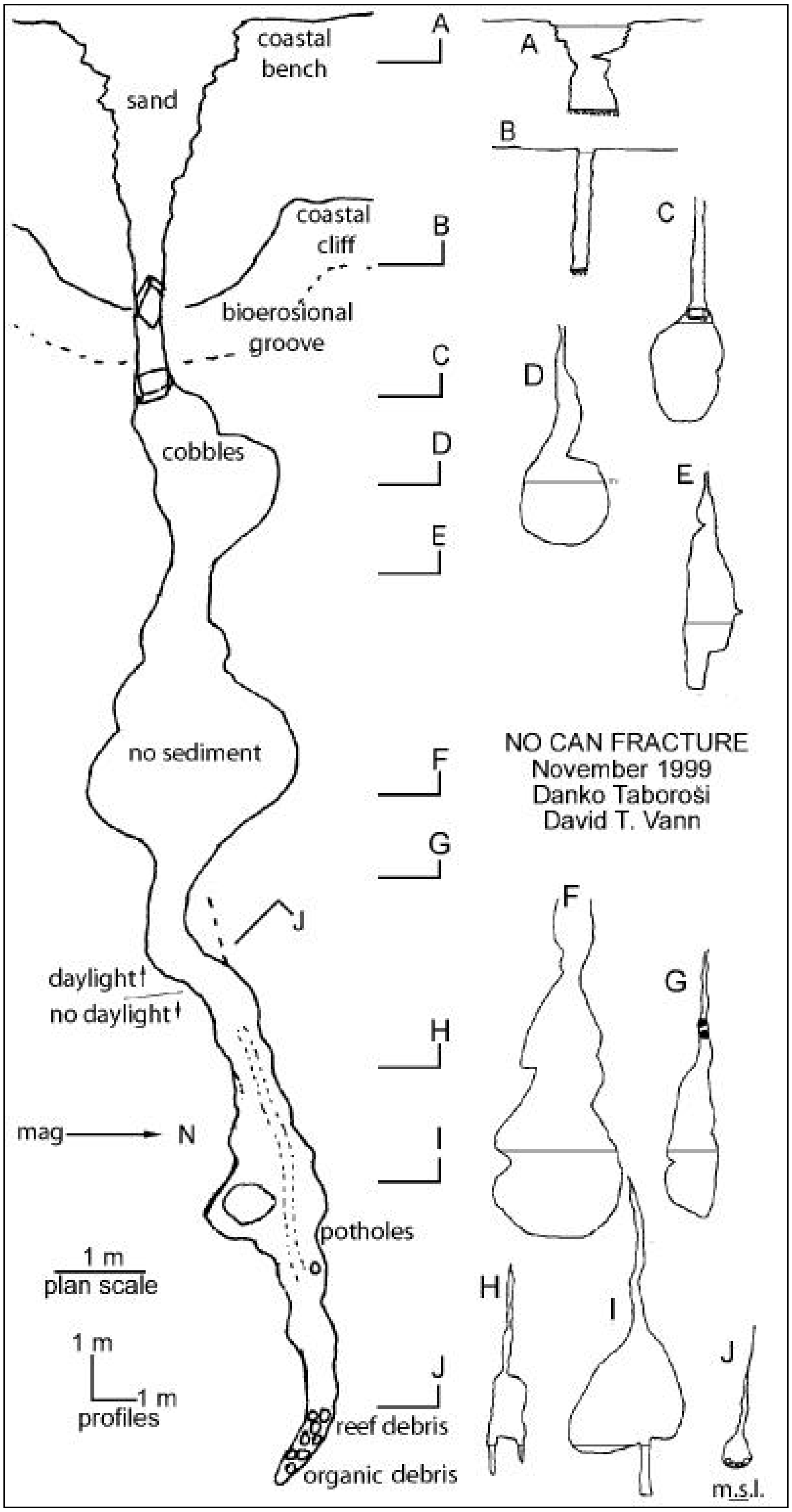

Figure 145: Map of No Can Fracture

Scott's Fracture

Scott’s Fracture is located 150 meters north of Menpachi Fracture. The cliff-face at this location is about 7 meters away from the ocean, behind an algal terrace at the sea level. The fracture cuts through the terrace and forms a 0.5- m-wide, slightly-meandering channel opening to the sea. The fracture is about 3 meters deep, widening to about a meter at the bottom, which is covered by sand deposits. Inland from the 7-m-long channel through the algal terrace, the fracture continues into the coastal cliff and is traversable for six additional meters. Freshwater appears to be coming from two smaller fractures feeding the large fracture. Estimated discharge is 11 l/s (0.25 mgd) (Jocson, 1998).

Pit Caves

Two Lovers' Point Pit Cave

The most spectacular and well-known pit cave on Guam is the Two Lovers Point Pit Cave. It is easily observed thanks to the bridge built over it as part of the development of Two Lovers’ Point as a tourist attraction. It is roughly elliptical in diameter and reaches a depth of 50 meters. It is entirely within Mariana Limestone detrital facies (Qtmd) and has well-developed vertical fluting on the walls.

Stream Caves

Mataguac Mud Cave

Mataguac Mud Cave is located in a sinkhole on the southwest flank of Mataguac Hill and is more complex. The active passage is traversable for 27.5 meters, with the floor entirely covered by mud, organic debris and limestone rubble. Contact between volcanic basement and limestone is discernible in the cave walls. This cave shows two levels of passage development: an active vadose cut canyon and a parallel dry phreatic tube above it. Interpretation of the top passage as a phreatic tube is based on the nearly perfect elliptical cross-section of the tubular passage, extensive fine sediment deposits throughout and smooth dissolution features in the walls. The two passages connect in several places where the phreatic tube floor has collapsed and opened it to the underlying vadose passage. There are two possible explanations for the presence of a phreatic tube in this typical vadose cave. It is likely that the initial horizon of cave development started out as a phreatic tube when flow was slow and the proto-passage full of water. As the passage enlarged and true conduit flow developed, downcutting began and new vadose passages under-drained the initial phreatic system (J. Mylroie, pers. comm.). It is also possible that the phreatic tube is actually younger than the vadose passage underneath: since the cave is fed by allogenic recharge it is subject to occasional heavy flooding which may overwhelm the vadose passage and activate phreatic passage above (J. Mylroie, pers. comm.).

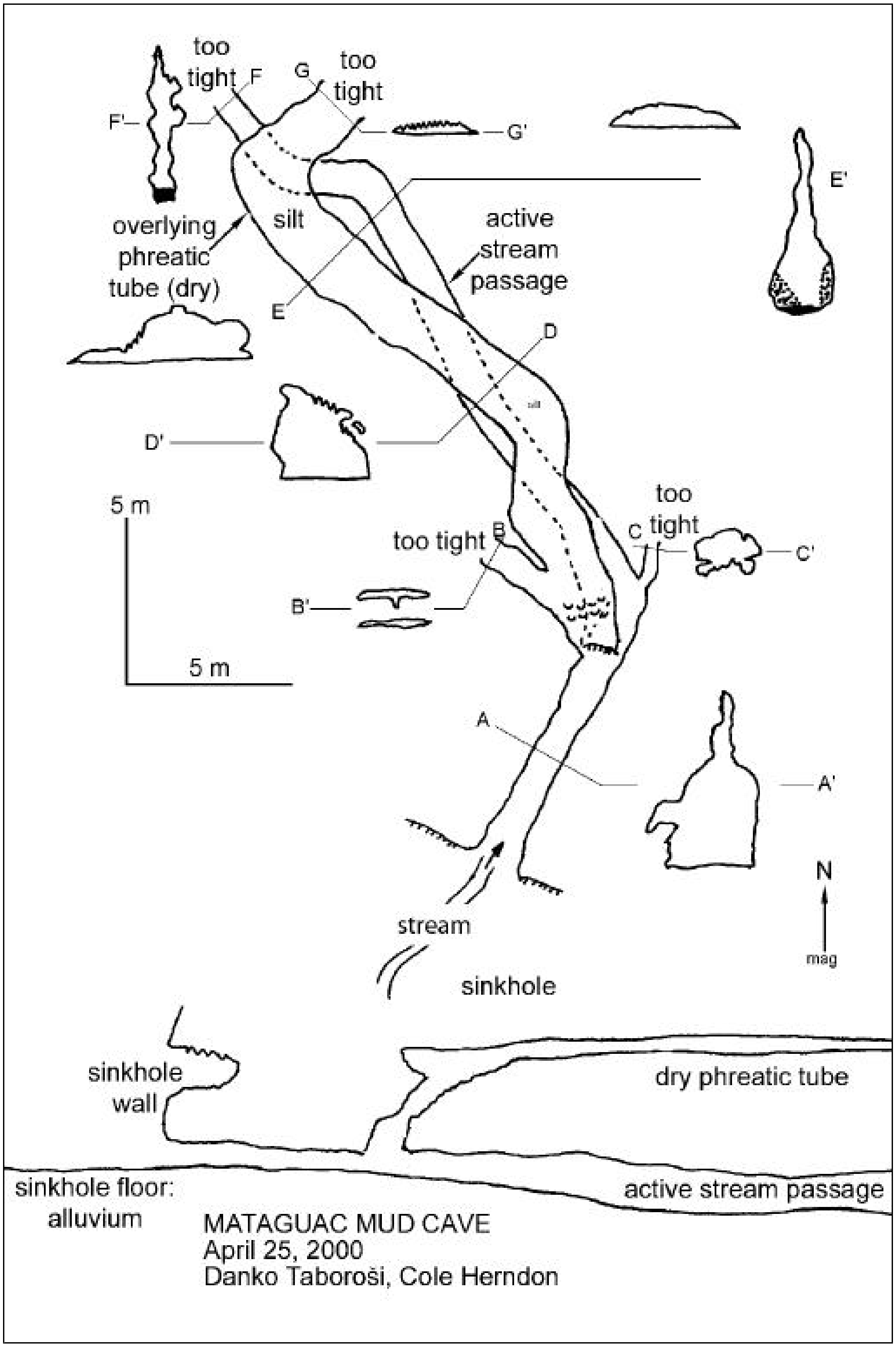

Figure 146: Map of Mataguac Mud Cave

North Mataguac Cave

North Mataguac Cave is probably similar to the two described above, but was not explored. Unfortunately, the entrance to this cave was destroyed by infilling on April 9, 2000 during construction activities on the north slope of Mataguac Hill. Because this cave is an active swallet for allogenic water captured by Mataguac Hill, its infilling causes obvious risks of flooding as well as collapse of structures built on the fill.

Caves of Unknown Origin

Lafac-Anao Collapse 3

The largest collapse area is the Lafac-Anao Collapse #3, which is 150 meters tall and 300 meters wide and extends to the top of the coastal cliff. This collapse area has several cave entrances at its northern end. In Lujuna area, there are two major collapse areas (southern one being 60 meters tall by 230 meters wide and the northern one 95 meters tall by 120 meters wide). Both have remnants of caves at the coast immediately adjacent to them.

Pagat Sea Arch

An example of a natural arch formed by collapse of a sea cave can be seen just south of Haputo Beach. It is a low arch and is best seen from the land. Several other natural arches, whose origin (flank margin cave vs. sea cave) is not clear, are located on the east coast, between Pagat and Anao. A typical representative of these is Pagat Arch at the coastline near Pagat Cave

SOUTHERN COAST

Abandoned Stream Caves

Gumayas Caves

The Gumayas Caves are located in the Togcha River Gorge (p. 27), near the stream, but hidden by vegetation. They are on the north side of the river, south of the narrowest part of the gorge. Look closely for faint trails or trail markers. The larger of the two caves, Gumayas Guma'Yu'us Cave, has a large domed room containing remnants of an altar. It was used as a church by the Chamorro population during WWII, and as a field hospital by the Imperial Japanese Army in late 1944. The second cave, Gumayas Chiget Cave, is located 46m downstream. It is a tubular, U-shaped passage, about 12m long.

Talofofo Cave #2

Talofofo Cave #2 is a series of four adjacent chambers. Entrance to the cave is through a steep 10 m long tube containing an additional small entrance and leading to a circular room, 8 m in diameter. This first room is dominated by six massive columns that nearly partition it. The floor is covered by cobbles, soil and flowstone, with the latter being a false floor collapsed in two places. Space below the false floor is not traversable. This chamber opens to the north, connecting to the second circular room, about 7 meters in diameter. The second room has few speleothems, small bell holes in the ceiling and a collapsed flowstone false floor revealing mud floor underneath. A single column in the northeast end marks the entrance to the third room. This room is oval in plan (9 m by 12 m) and well decorated by flowstone deposits. It is nearly split into two by three columns. The first portion of the room leads to a steep, flowstone covered passage, sloping about 36o upward to the cave's third entrance. This passage appears to have developed along a fracture and probably received significant inflow. The portion of the room behind the column partition leads to a 13-m long, down-sloping, narrow passage 1.5-2 m wide, and well decorated by stalactites and columns. An additional elongate room (15 m by 4-6 m) can be accessed beyond the third chamber through a very tight squeeze through a column/flowstone partition in the north wall. The back of the cave contains a shallow pool of perched water, numerous small stalactites and a short flowstone floored passage.

Talofofo Caves

Several large caves in southern Guam are stream caves made by voluminous runoff that has since been diverted. Today these caves are dry, only occasionally receiving local rainwater input, but not runoff.

The best examples of this type are the Talofofo Caves, a popular hiking destination and an extensive cave system located in the Mariana Limestone reef facies cliff overlooking Talofofo Bay. The seven caves in the complex are high ground today and can receive water only from the rain that falls right on top of them, but their size and shape indicates that they were once receiving extensive stream input. The caves and one natural arch are clustered around two collapse sinkholes at the top of a limestone ridge. Four of the caves are small, single room or tube passages with soil floors and little or no decorations. These were listed by Rogers and Legge (1992) as Talofofo Caves #s 1, 4, 5 and 6. The remaining three are more significant and include a well-decorated cave containing several large connected chambers (Talofofo Cave #2), a long tubular cave extending through the limestone ridge and terminating in an opening in the face of the cliff overlooking the ocean (Talofofo Cave #3), and a large 32 m pit cave with two entrances and additional horizontal passages half way down the pit (Talofofo Pit Cave). This last cave is the largest in the complex but was curiously not mentioned by Rogers and Legge (1992) in their compendium.

Talofofo Cave #3 is a tubular passage starting from a collapse sinkhole on the southeast side of the limestone ridge. The passage leads through the ridge and opens in the cliff face on the opposite end, overlooking the ocean. Curiously, the passage steeply slopes towards the northwest, indicating flow of water from the direction of the present coastline towards the island interior. The water used to come from the cave entrance presently in the cliff, lacking any surface whatsoever that could capture the flow.

Rogers and Legge (1992) write that Talofofo Caves had a "relatively simple history" and interpret them as phreatic dissolution features, made by diffuse flow. However, there is no evidence to support this interpretation. No phreatic dissolution features are visible anywhere in the caves; long and steep tubular passages are indicative of conduit flow; and finally, a 32 meters deep pit cave is certainly an unlikely result of phreatic dissolution. Interpretation as stream caves is more supported by cave morphology, although the source of enough focused discharge is not obvious. It is possible that the caves developed as conduits draining central Guam volcanic areas, through the limestone ridge, into the ocean. Central Guam terrain was subsequently lowered and runoff pirated by Talofofo River, leaving the caves as dry high ground. Gumayas Caves, located in the Togcha River gorge may be another example of abandoned stream caves.

Banana Hole

Ito and Minagawa Sink

An interesting collapse sinkhole reminiscent of banana holes (Harris et al., 1995) occurs in a Bonya Limestone outcrop north of Togcha river. Known as Ito and Minagawa Sink, it is about 10 meters deep and contains a shelter cave, infilled by collapse materials, gravel and sand. The cave was used as a shelter by two Japanese soldiers, Ito and Minagawa, following World War II. If this sinkhole is indeed a banana hole, it is a unique in sense that it has developed in a local water table within a small limestone outcrop surrounded by argillaceous rocks, and not in an extensive freshwater lens.

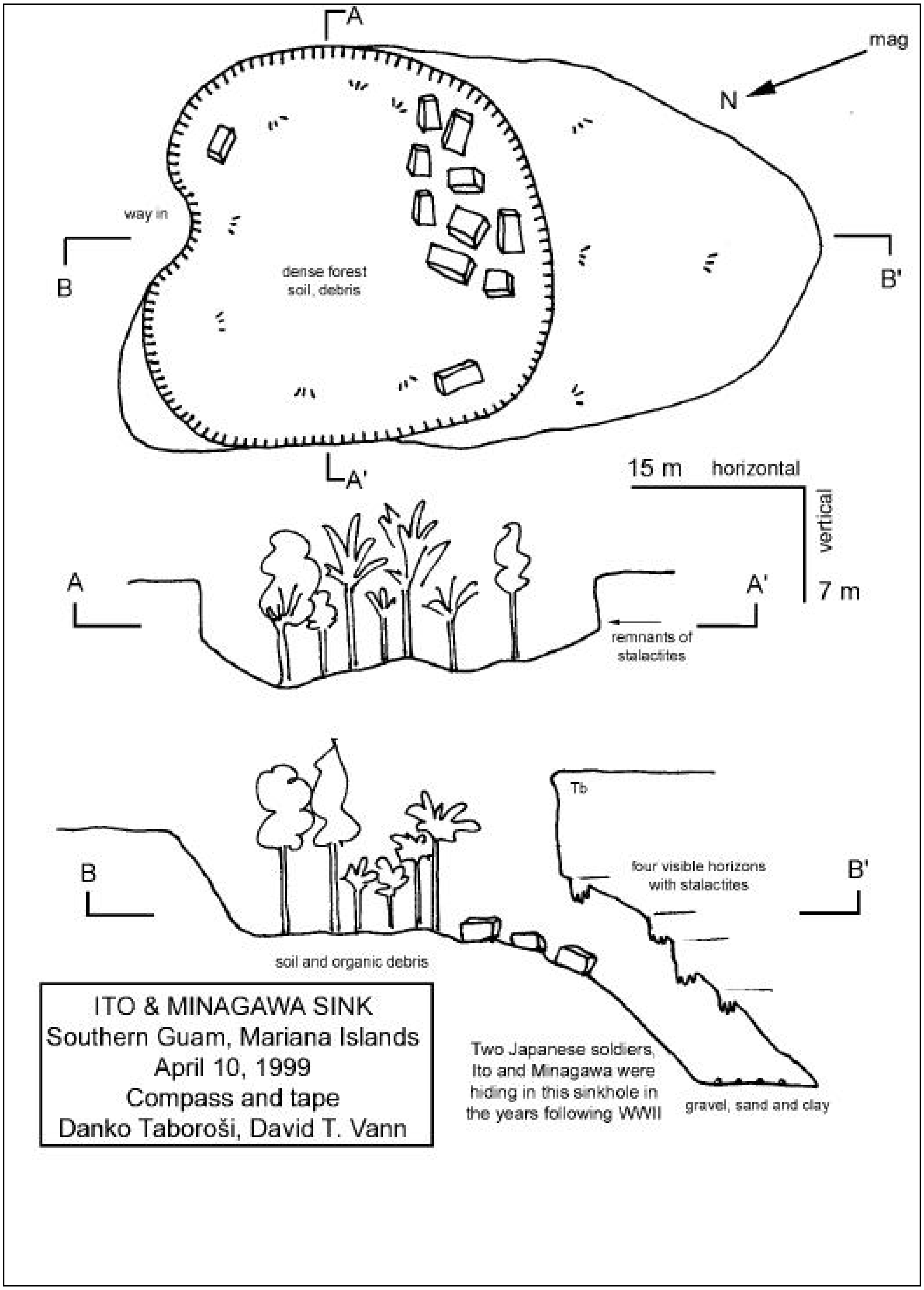

Figure 147: Map of Ito & Minagawa Sink

Flank Margin Caves

Adjoulan Point Cave, Asquirogo Cave, Matala Caves, and Tres Botsas

There are numerous flank margin caves along the east coast of southern Guam. Most known caves are located in the cliffs on the north side of Talofofo Bay (Adjoulan Point Cave, Asquiroga Cave, four Matala Caves and three caves at Tres Botsas). Entrances to all of these single-chambered caves are located in cliff faces. On the south side of Talofofo Bay, a prominent massive stalagmite overhanging the Gayloup Cove is probably a leftover of a flank margin cave all but destroyed by cliff retreat.

Asanite Cave

Asanite Cave is located at the base of the cliff at Asanite Point. The cave has no limestone bedrock and is floored entirely by a steep pile of collapse blocks and some flowstone developed over the collapse. Located near the sea level, the cave intersects the groundwater and has extensive submerged passages. Snorkeling in the cave revealed a depth of submerged chambers of at least 8 meters. This cave is very similar to Marbo and Fadian Fish Hatchery caves from northern Guam. Like in the case of similar northern caves, Asanite Cave is located just inland from a conspicuous cove developed between Asanite and Ypan Points. Two undescribed species of atyid shrimp have been recorded in Asanite Cave. They are red or pink in color, up to 18 mm long and blind (B. Tibbatts, pers. comm.) There are additional collapsed caves and sinkholes located in the village of Ypan and in the forest west of it.

Mata Caves

Cliffs in Anaga area, behind the village of Ypan probably have several flank margin caves. Mata Cave and the nearby shelter caves behind Notre Dame School in the Mata area of Talofofo are probably also of flank margin origin.

Orote Grottos

Cliffs of Orote Peninsula also show several cave entrances, probably flank margin in origin. The largest phreatic voids in Orote Peninsula are the Orote Grottos. Located at the south end of the south side of Orote Peninsula, these two adjacent, extremely large phreatic chambers were breached by wave erosion and probably expanded by partial collapse.

Orote Window

There are several natural arches made by collapse of flank margin caves (or sea caves) in southern Guam. None are as spectacular as the examples from the east coast of northern Guam. A small arch has developed on the small reef island near Tipoco cemetery in Inarajan. Another small arch, Orote Window, made by partial collapse of a flank margin cave, is visible near the top of the cliff on the south side of Orote Peninsula.

Pit Caves

Blue Hole

The best know submerged pit cave and one of Guam's most popular dive sites is the Blue Hole, located off the southern coast of Orote Peninsula. It is a vertical shaft, opening on a reef flat at a depth of 20 meters. The shaft extends to about 95 meters below sea level. At a depth of 40 meters, a large window opens in the outer wall of the shaft allowing the diver to exit that way. Additional submerged shafts have been reported from northern Guam but none could be confirmed during this study.

Talofofo Pit Cave

Pit caves may also develop with no opening to the surface, created by vadose water from the epikarst rather than the surface, in which case they represent significant geologic hazards (Mylroie and Carew, 1997). Triple Shaft Cave (Mylroie and Carew, 1997) in the Bahamas is one example. It is unknown whether such caves exist in the interior of northern Guam plateau. However, remnants of pit caves with no surface opening can be seen along some coastal cliffs in northern Guam, particularly the cliff parallel to the beach at Ritidian. They have been exposed by cliff retreat and appear to have been parts of larger caves. In southern Guam, one of the Talofofo caves is a 33-meter deep pit cave, completely roofed over by limestone bedrock. Another (collapsed) cave in the Talofofo cave complex has an 11-meter vertical shaft in its walls, also not open to the surface.

SOUTHERN INTERIOR BASIN

Mixing-zone Fracture Caves

Bay Rum Cave

A large number of caves have been reported from the Naval Magazine area. No extensive fieldwork took place there during this project and only a few caves were investigated. Rogers and Legge (1992) give a detailed description of Bay Rum Cave (a.k.a. Bay Leaf Cave) that appears to be a 172 m long, fracture guided cave, developed in Alifan Limestone. They further mention unexplored Hoyu Sabana Lamlam, Mt. Almagosa Cave and Pinnacle Cave (in the Alifan Limestone ridge) and Ibaba Cave, Liyang Namu Kanutu Cave and Hoyu Fena (in Bonya Limestone northeast of the Fena Lake).

Stream Caves

Fena Sinkhole Cave

A good example of an ephemeral stream cave is Fena Sinkhole Cave, located in a cockpit doline east of Tolae Yu'us River resurgence. The entrance to the cave is at the bottom of the doline. The cave passages contain thick alluvial deposits. Branches and other plant material and fresh organic debris were found in some of the passages in this cave, clear evidence of a recent storm water flow. Most of the main passage is large and tall enough to comfortably walk through. At its end, the passage becomes only about 0.5 m high, containing extensive stalactite development in a ceiling so low that the stalactites are partially embedded in floor mud deposits. Passage on the other side of this crawlway leads to an entrance opening at the bottom of the neighboring doline. This cave is a connection between the bottoms of two cockpit dolines and runs through Bonya limestone ridge separating them. It conducts water from one doline to another during high rainfall events.

Lost River Rise Cliff Cave

An abandoned cave, Lost River Rise Cliff Cave, was located about 4 meters above the Tolae Yu'us River resurgence. It is entered through an opening in the cliff and could represent a former river resurgence before the local base level was lowered. The cave is traversable for about 20 meters. It shows indications of having contained extensive sediment deposits upon which layers of flowstone have developed. The sediment has been subsequently removed, and the flowstone deposits indicate previous sediment level.

SOUTHERN MOUNTAIN RANGE

Abandoned Stream Cave

Liyang Almagosa Gelagu

Liyang Almagosa Gelagu (also known as the North Almagosa Cave) is located some 30 meters north of Almagosa Spring. It is a dry cave, containing a few stalactites and flowstone deposits, with soil covering most of the floor. Tubular passages of this cave, some 20 meters long in total, are probably abandoned stream conduits, once part of the Almagosa Cave system.

Nimitz Hill Collapse Sink #1

Two inventoried depressions and numerous other shallow depressions occur within the Alifan Limestone outcrop on Nimitz Hill, immediately south of the Pago-Adelup fault. Being adjacent to a major geologic fault, this area is heavily faulted and fractured and contains numerous traversable fracture caves. The alignment of caves and depressions along faults is evident in the field. Depressions here are collapse dolines whose walls are often part linear following orientation of faults and fractures.

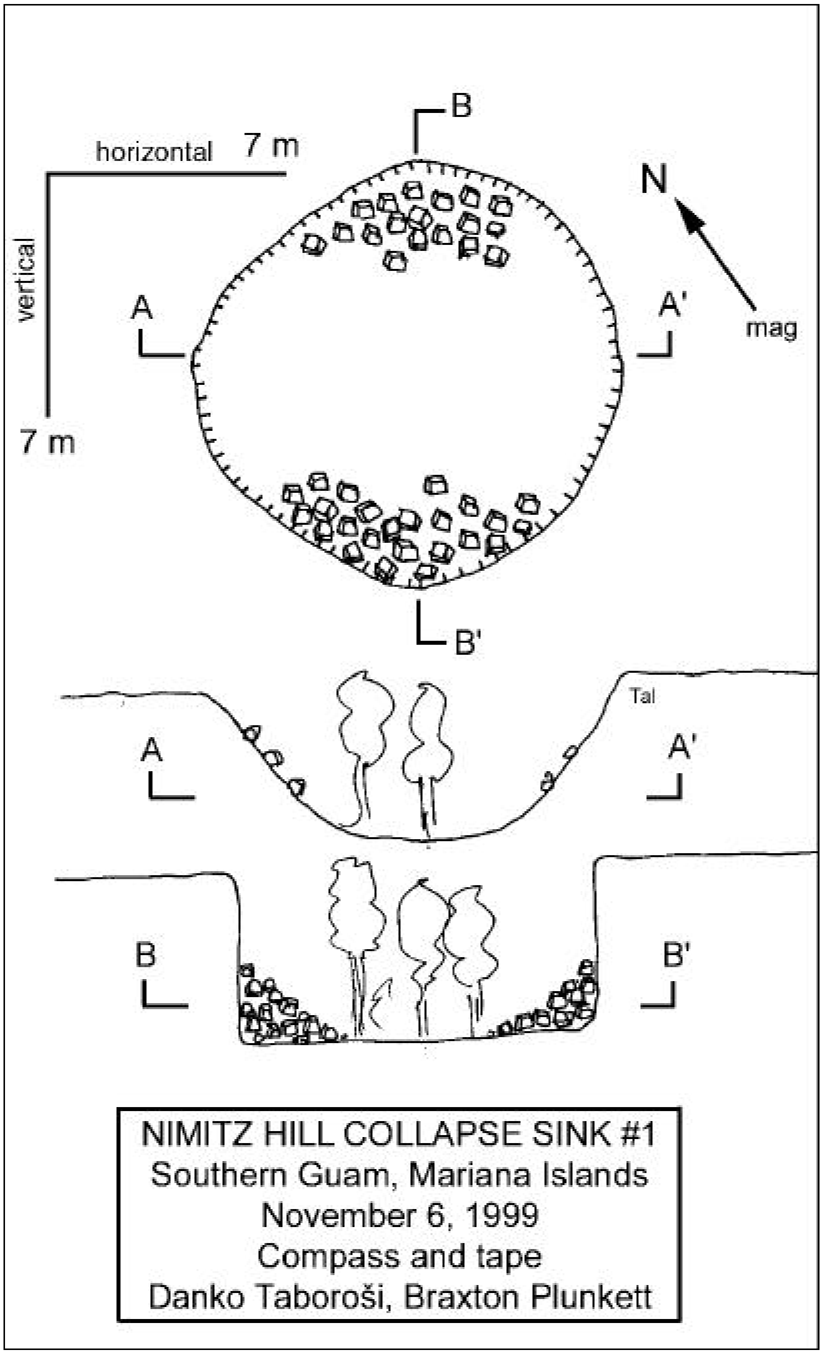

Figure 148: Map of Nimitz Hill Collapse Sink #1

Nimitz Hill Collapse Sink #2

Two inventoried depressions and numerous other shallow depressions occur within the Alifan Limestone outcrop on Nimitz Hill, immediately south of the Pago-Adelup fault. Being adjacent to a major geologic fault, this area is heavily faulted and fractured and contains numerous traversable fracture caves. The alignment of caves and depressions along faults is evident in the field. Depressions here are collapse dolines whose walls are often part linear following orientation of faults and fractures.

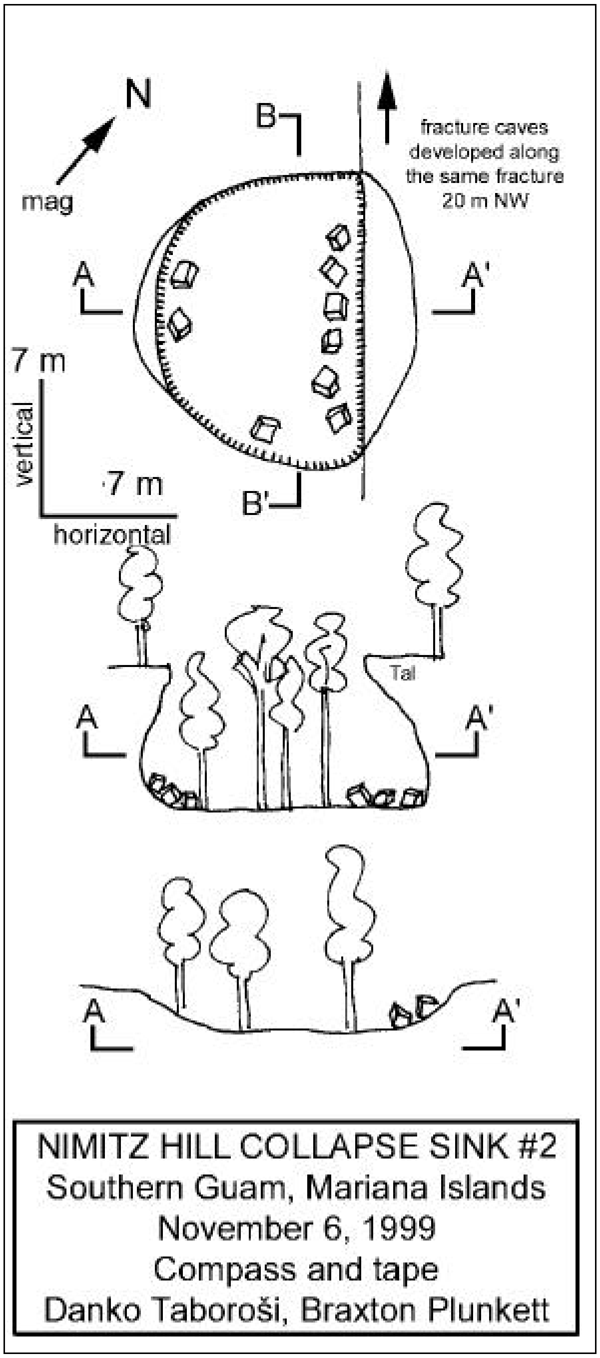

Figure 149: Map of Nimitz Hill Collapse Sink #2

Flank Margin Cave

Anae Caverns

Perhaps the best know submarine caves on Guam are Anae Caverns. A popular diving destination, Anae Caverns are located at a depth of about 10 meters, at Anae Island off the coast of Agat. These shallow and open caves are probably submerged flank margin chambers.

Mixing-Zone Fracture Caves

Japanese Caves

Japanese Cave, located in the jungle across from the Department of Defense High School on Nimitz Hill, can be considered representative of caves found in Nimitz Hill area because it shows all complexity and variety of genetic factors involved in their making. It is a small but genetically complex cave showing evidence of vadose and phreatic dissolution as well as collapse. The cave has two entrances, both results of collapses along a NW-SE trending fault.

The northwest entrance leads to a large day lit collapse chamber. The chamber contains numerous boulders and rubble, all the result of collapse, and has abundant but small tufaceous stalactites. The second room is smaller and deeper and is entered through a short passage in the west part of the large chamber. The northeastern half of the ceiling in this room is flat and follows a fracture, while the other half has been stable longer and shows extensive stalactite development. Consequently, the floor in the northeast end is covered by rubble, while the opposite side of the room has several large stalagmites. Interesting phreatic dissolution features found in the southwestern wall are evidence of this cave's complex history and modification in a phreatic environment. Enlargement of this room and cave in general as a result of phreatic dissolution, possibly flank margin type, cannot be excluded.

The cave's southeast entrance leads to a large passage clearly developed along a fault, dipping about 30°. The cave appears as a series of small chambers, due to extensive stalactite/stalagmite partitions, but is really a single large planar passage, developed along a fault. Low portions in the cave show accumulations of fine sediment. A short horizontal plane passage leads from the ceiling and possibly indicates a stable former water table level.

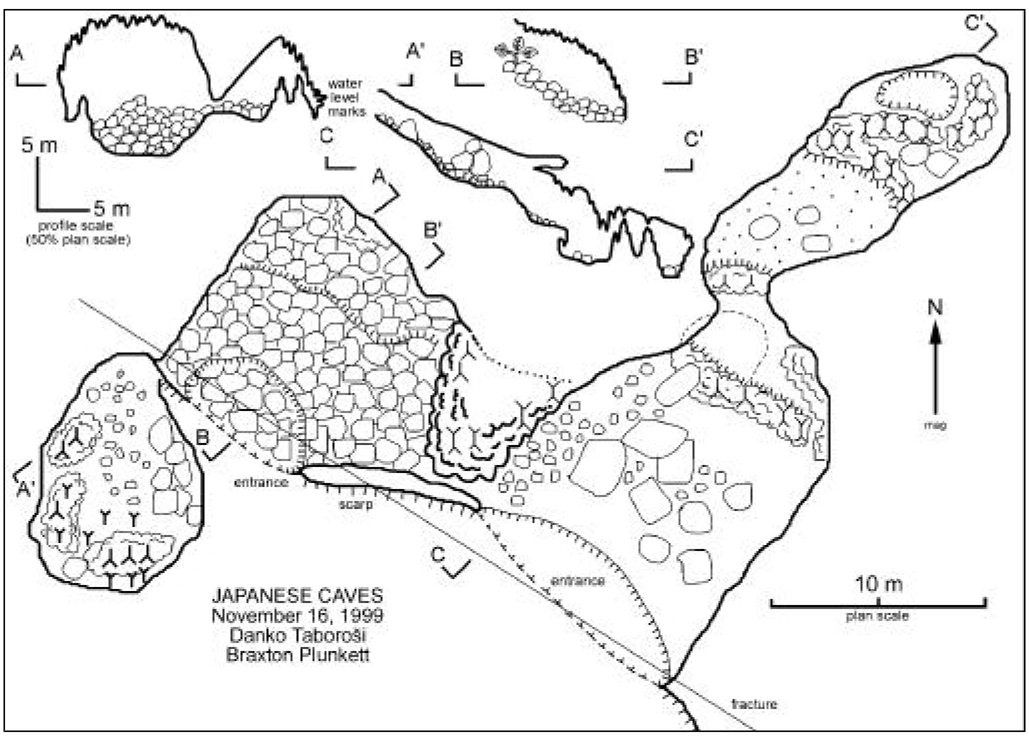

Figure 150: Map of Japanese Caves

Stream Cave

Almagosa Cave

The best example of this type is Almagosa Cave, located on the eastern slope of Mt. Almagosa west of the Fena Lake. The cave entrance is at Almagosa Spring, a flashy spring discharging water collected by the Alifan Limestone mountain ridge. Nearby Chepak Spring, about 65 meters away, provides an additional entrance to this cave (C. Wexel, pers. comm.). A low, muddy, active stream passage leads from the Almagosa Spring entrance. It is up to a 1.5 meters high, up to few meters wide. The floor of the passage is comprised of limestone bedrock and not volcanic rocks, although they must be quite shallow. Limestone on the floor of the stream passage is extremely jagged, shaped by mechanical erosion as well as dissolution. Small, non-traversable tributary conduits join the main stream passage at a right angle, their ephemeral flows cutting well-developed vertical flutings in the main passage walls. This portion of the stream passage almost certainly becomes completely flooded during high discharge episodes. After about 10 meters from the cave entrance, the passage becomes high enough to allow walking. Further upstream, the main passage continues as a large phreatic tube up to a total length of 65 meters where it is sealed by a siphon. By swimming through the siphon (a practice not recommended due to murky water and risk of disorientation) it is possible to reach the beautifully decorated and rarely visited continuation of the main passage. This stream passage ends after 100 meters from the siphon, fully obstructed by an underwater mud plug. Total length of the main stream passage is thus about 165 meters, and total survey length that includes side passages is about 250 meters (C.

Wexel, pers. comm.) It is likely that additional unexplored passages exist in this cave. This well decorated active stream cave is an unusual karst feature on a carbonate island, more typical of continental settings. It was not explored in detail due to time and access restrictions and the fact that the focus of the study was on northern Guam. A map of this cave is currently in preparation (Wexel, in prep.)

Caves of Unknown Origin

Nimitz Hill Shelter Caves

The Alifan Limestone block south of the Pago-Adelup fault, known as Nimitz Hill, is extremely rich in caves. This is a tectonically active, heavily faulted, and fractured area. Although Tracey et al. (1964) mapped only two joints in this area, there are many more. A simple walk over this terrain reveals a large number of joints, often dissolutionally enlarged and appearing as 2-3 meter deep fissures, large enough for a person to move through. Faults are also common and have not yet been mapped. Fractures, also, are often dissolutionally enlarged and frequently contain shelter caves. Some examples of such shelter caves are illustrated. Numerous large and more complex caves in the area also show strong control by fractures and are presumably made by extensive enlargement of fractures.

Since enlargement of fractures seems to be the strongest genetic factor, these caves, very different from caves elsewhere on Guam, are discussed here under the designation of "fracture caves." They may or may not be related to "fracture caves" described by Mylroie and Carew (1995). The development of fracture caves on Guam seems to be much more complex than simple modification of sites of mechanical failure by groundwater. Development of fracture caves in Guam's Nimitz Hill area is probably influenced by shallow volcanic basement, allogenic catchment from nearby volcanic terrane, collapse events, past sea level and groundwater lens positions (as indicated by rare wall cusps and other phreatic dissolution features in some caves) in addition to enlargement of fractures.

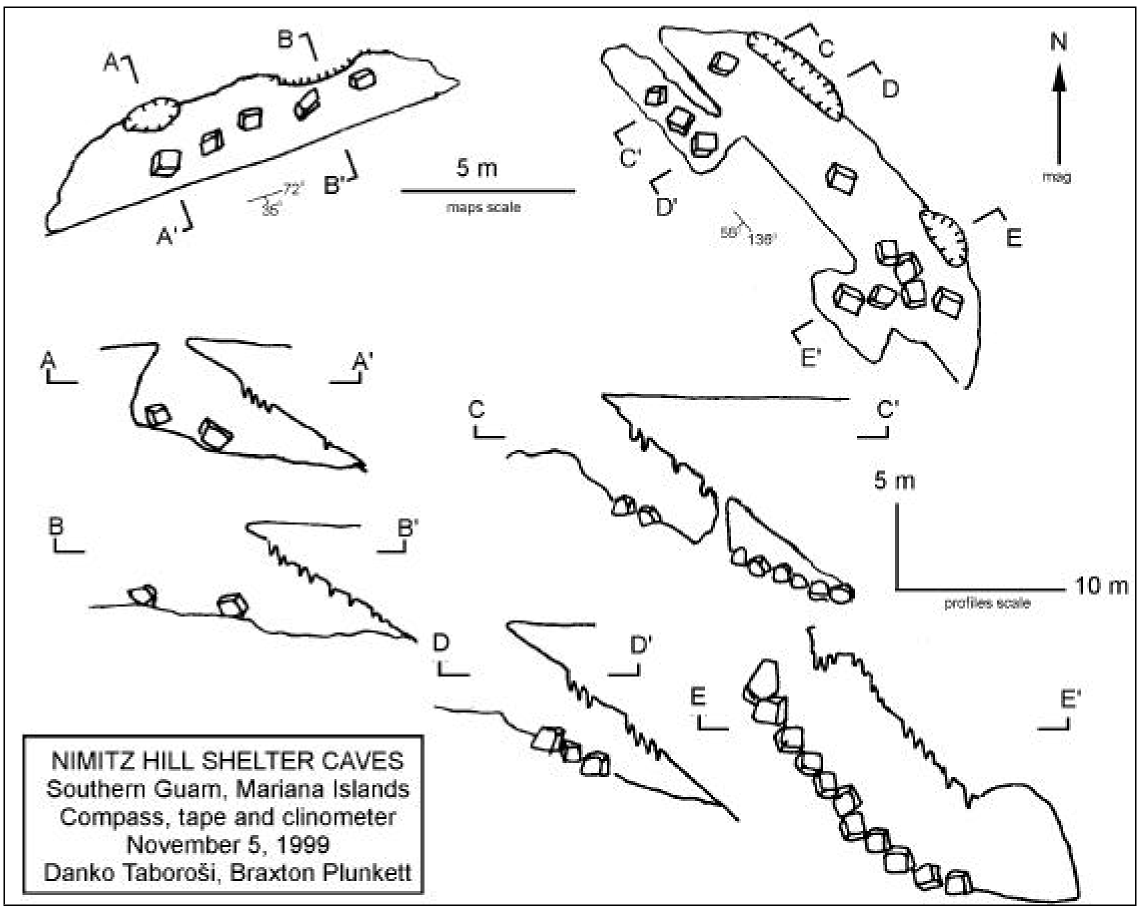

Figure 151: Map of Nimitz Hill Shelter Caves

Table 19: Alphabetic list of the inventoried karst features of Guam

Karst Feature Name	Province	Karst Feature Type
7 Little Springs	Northern Plateau	Discharge Feature
AAB 6th St Pit	Northern Plateau	Closed Depression
AAFB 1st St Depression	Northern Plateau	Closed Depression
AAFB 33rd St borrow pit	Northern Plateau	Closed Depression
AAFB 5th St Pit	Northern Plateau	Closed Depression
AAFB Injection wells depression	Northern Plateau	Closed Depression
AAFB NE of 1st St depression	Northern Plateau	Closed Depression
AAFB NW Perimeter Rd depression	Northern Plateau	Closed Depression
AAFB Perimeter road depression	Northern Plateau	Closed Depression
AAFB Pipeline borrow pit	Northern Plateau	Closed Depression
Adelup Cave	Northern Plateau	Flank Margin Cave
Adjoulan Point Cave	Southern Coast	Flank Margin Cave
Agafo Gumas (north of) depression	Northern Plateau	Closed Depression
Ague 1	Northern Plateau	Discharge Feature
Ague 2	Northern Plateau	Discharge Feature
Ague Cove	Northern Plateau	Discharge Feature
Ague Cove Cave	Northern Plateau	Discharge Feature
Ague Sea Cave	Northern Plateau	Sea Cave
Alifan ridge sink 1	Southern Mountain Range	Closed Depression
Alifan ridge sink 2	Southern Mountain Range	Closed Depression
Alifan ridge sink 3	Southern Mountain Range	Closed Depression
Alifan ridge sink 4	Southern Mountain Range	Closed Depression
Alifan ridge sink 5	Southern Mountain Range	Closed Depression
Almagosa Cave	Southern Mountain Range	Stream Cave
Amantes Cliff Caves	Northern Plateau	Unknown Origin
Amantes Point Cave	Northern Plateau	Flank Margin Cave
Amantes1	Northern Plateau	Discharge Feature
Amantes2	Northern Plateau	Discharge Feature
Anae Caverns	Southern Mountain Range	Flank Margin Cave
Anae Island Cave	Southern Mountain Range	Flank Margin Cave
Anao depression	Northern Plateau	Closed Depression
Anao Point Cave	Northern Plateau	Flank Margin Cave
Anao Point Collapse	Northern Plateau	Unknown Origin
Anao Tunnel	Northern Plateau	Unknown Origin
Apusento Gardens sink (a)	Northern Plateau	Closed Depression
Apusento Gardens sink (b)	Northern Plateau	Closed Depression
Arch	Northern Plateau	Discharge Feature
Asalonso Cave	Southern Coast	Unknown Origin
Asan depression 1	Southern Mountain Range	Closed Depression
Asan depression 2	Southern Mountain Range	Closed Depression
Asanite Cave	Southern Coast	Flank Margin Cave

Table 19 (Continued)

Karst Feature Name	Province	Karst Feature Type
Asanite Road Caves	Southern Coast	Flank Margin Cave
Asanite sink	Southern Coast	Closed Depression
Asdonlucas Cave	Northern Plateau	Flank Margin Cave
Asdonlucas sink 1	Northern Plateau	Closed Depression
Asdonlucas sink 2	Northern Plateau	Closed Depression
Asiga Cave	Southern Coast	Flank Margin Cave
Aspengo depression 1	Northern Plateau	Closed Depression
Aspengo depression 2	Northern Plateau	Closed Depression
Aspengo depression 3	Northern Plateau	Closed Depression
Aspengo main depression	Northern Plateau	Closed Depression
Asquiroga Cave	Southern Coast	Flank Margin Cave
Assupian Cave	Southern Coast	Unknown Origin
Awesome Cave	Northern Plateau	Contact Cave
Awesome sink	Northern Plateau	Closed Depression
Barrigada depression 1	Northern Plateau	Closed Depression
Barrigada depression 2	Northern Plateau	Closed Depression
Barrigada depression 3	Northern Plateau	Closed Depression
Barrigada depression 4	Northern Plateau	Closed Depression
Barrigada depression 5	Northern Plateau	Closed Depression
Barrigada sink	Northern Plateau	Abandoned Stream Cave
Bay Rum Cave	Southern Interior Basin	Mixing-zone Fracture Cave
Beach Rock Spring	Northern Plateau	Discharge Feature
Blue Hole	Southern Coast	Pit Cave
Bonya River Arch	Southern Interior Basin	Unknown Origin
Bonya river sink 1	Southern Interior Basin	Closed Depression
Bonya river sink 2	Southern Interior Basin	Closed Depression
Bonya river sink 3	Southern Interior Basin	Closed Depression
Bonya-Tolae Yu'us river	Southern Interior Basin	Closed Depression
Brecciated zone depression 1	Northern Plateau	Closed Depression
Brecciated zone depression 10	Northern Plateau	Closed Depression
Brecciated zone depression 11	Northern Plateau	Closed Depression
Brecciated zone depression 12	Northern Plateau	Closed Depression
Brecciated zone depression 13	Northern Plateau	Closed Depression
Brecciated zone depression 14	Northern Plateau	Closed Depression
Brecciated zone depression 15	Northern Plateau	Closed Depression
Brecciated zone depression 2	Northern Plateau	Closed Depression
Brecciated zone depression 3	Northern Plateau	Closed Depression
Brecciated zone depression 4	Northern Plateau	Closed Depression
Brecciated zone depression 5	Northern Plateau	Closed Depression

Table 19 (Continued)

Karst Feature Name	Province	Karst Feature Type
Brecciated zone depression 6	Northern Plateau	Closed Depression
Brecciated zone depression 7	Northern Plateau	Closed Depression
Brecciated zone depression 8	Northern Plateau	Closed Depression
Brecciated zone depression 9	Northern Plateau	Closed Depression
Callon Tramojo ponding basin 1	Northern Plateau	Closed Depression
Callon Tramojo ponding basin 2	Northern Plateau	Closed Depression
Carino Sink Cave	Northern Plateau	Abandoned Stream Cave
Castro's Beachrock Spring	Northern Plateau	Flank Margin Cave
Catalina point depression	Northern Plateau	Closed Depression
Chalan Pago Cave	Northern Plateau	Flank Margin Cave
Chalan Pago uvala	Northern Plateau	Closed Depression
Coconut Crab Cave	Northern Plateau	Discharge Feature
Collapse south of Pati	Northern Plateau	Unknown Origin
Cool Cave	Southern Coast	Flank Margin Cave
County Club depression	Southern Coast	Closed Depression
Dededo golf course ponding basin 1	Northern Plateau	Closed Depression
Dededo golf course ponding basin 2	Northern Plateau	Closed Depression
Dededo Jr. High School depression	Northern Plateau	Closed Depression
Dededo small depression 1	Northern Plateau	Closed Depression
Dededo small depression 2	Northern Plateau	Closed Depression
Depression behind GCC	Northern Plateau	Closed Depression
Devil's Punchbowl	Northern Plateau	Flank Margin Cave
Elvis' Pelvis Cave	Northern Plateau	Stream Cave
Evian Cave	Northern Plateau	Discharge Feature
Exxon sink	Northern Plateau	Closed Depression
Fadian borrow pit 1	Northern Plateau	Closed Depression
Fadian borrow pit 2	Northern Plateau	Closed Depression
Fadian borrow pit 3	Northern Plateau	Closed Depression
Fadian borrow pit 4	Northern Plateau	Closed Depression
Fadian Cove Spring	Northern Plateau	Discharge Feature
Fadian depression	Northern Plateau	Closed Depression
Fadian Fish Hatchery Cave	Northern Plateau	Flank Margin Cave
Fadian Point Cave	Northern Plateau	Flank Margin Cave
Fafai Cave	Northern Plateau	Flank Margin Cave
Falcona High Cliff Cave	Northern Plateau	Flank Margin Cave
Fena cockpit sink 1	Southern Interior Basin	Closed Depression
Fena cockpit sink 10	Southern Interior Basin	Closed Depression
Fena cockpit sink 11	Southern Interior Basin	Closed Depression
Fena cockpit sink 12	Southern Interior Basin	Closed Depression
Fena cockpit sink 13	Southern Interior Basin	Closed Depression

Table 19 (Continued)

Karst Feature Name	Province	Karst Feature Type
Fena cockpit sink 14	Southern Interior Basin	Closed Depression
Fena cockpit sink 15	Southern Interior Basin	Closed Depression
Fena cockpit sink 16	Southern Interior Basin	Closed Depression
Fena cockpit sink 17	Southern Interior Basin	Closed Depression
Fena cockpit sink 18	Southern Interior Basin	Closed Depression
Fena cockpit sink 19	Southern Interior Basin	Closed Depression
Fena cockpit sink 2	Southern Interior Basin	Closed Depression
Fena cockpit sink 20	Southern Interior Basin	Closed Depression
Fena cockpit sink 21	Southern Interior Basin	Closed Depression
Fena cockpit sink 22	Southern Interior Basin	Closed Depression
Fena cockpit sink 23	Southern Interior Basin	Closed Depression
Fena cockpit sink 24	Southern Interior Basin	Closed Depression
Fena cockpit sink 25	Southern Interior Basin	Closed Depression
Fena cockpit sink 26	Southern Interior Basin	Closed Depression
Fena cockpit sink 27	Southern Interior Basin	Closed Depression
Fena cockpit sink 28	Southern Interior Basin	Closed Depression
Fena cockpit sink 29	Southern Interior Basin	Closed Depression
Fena cockpit sink 30	Southern Interior Basin	Closed Depression
Fena cockpit sink 31	Southern Interior Basin	Closed Depression
Fena cockpit sink 32	Southern Interior Basin	Closed Depression
Fena cockpit sink 4	Southern Interior Basin	Closed Depression
Fena cockpit sink 5	Southern Interior Basin	Closed Depression
Fena cockpit sink 6	Southern Interior Basin	Closed Depression
Fena cockpit sink 7	Southern Interior Basin	Closed Depression
Fena cockpit sink 8	Southern Interior Basin	Closed Depression
Fena cockpit sink 9	Southern Interior Basin	Closed Depression
Fena narrow sink	Southern Interior Basin	Closed Depression
Fena Sinkhole Cave	Southern Interior Basin	Stream Cave
Finagayan borrow pit 1	Northern Plateau	Closed Depression
Finagayan borrow pit 2	Northern Plateau	Closed Depression
Finagayan borrow pit 3	Northern Plateau	Closed Depression
Finagayan small depression 1	Northern Plateau	Closed Depression
Finagayan small depression 2	Northern Plateau	Closed Depression
Finagayan small depression 3	Northern Plateau	Closed Depression
Fonte Cave	Southern Mountain Range	Abandoned Stream Cave
Fountain	Northern Plateau	Discharge Feature
Frankie's Cave	Northern Plateau	Flank Margin Cave
Frank's Cave	Northern Plateau	Discharge Feature
Fujita	Northern Plateau	Discharge Feature
G. municipal golf course depr. 1	Northern Plateau	Closed Depression

Table 19 (Continued)

Karst Feature Name	Province	Karst Feature Type
G. municipal golf course depr. 2	Northern Plateau	Closed Depression
Gadao's Cave	Southern Coast	Flank Margin Cave
Gayinero sink a	Northern Plateau	Closed Depression
Gayinero sink b	Northern Plateau	Closed Depression
Golf Course Collapse	Northern Plateau	Unknown Origin
Grotto	Northern Plateau	Discharge Feature
Guacluluyao sink (north)	Northern Plateau	Closed Depression
Guacluluyao sink (south)	Northern Plateau	Closed Depression
Guam Observatory depression	Northern Plateau	Closed Depression
Guam Rock Products quarry	Northern Plateau	Closed Depression
Gugagon ponding basin	Northern Plateau	Closed Depression
Gugagon ponding basin 2	Northern Plateau	Closed Depression
Gumayas Chiget Cave	Southern Coast	Abandoned Stream Cave
Gumayas Guma'Yu'us Cave	Southern Coast	Abandoned Stream Cave
Gumoje Cave	Southern Coast	Unknown Origin
Gun Beach1	Northern Plateau	Discharge Feature
Gun Beach2	Northern Plateau	Discharge Feature
H. Rock Quarry N. Sink Caves	Northern Plateau	Mixing-zone Fracture Cave
H. Rock Quarry S. Sink Caves	Northern Plateau	Mixing-zone Fracture Cave
Haputo Cave	Northern Plateau	Flank Margin Cave
Haputo Collapsed Cave	Northern Plateau	Flank Margin Cave
Haputo radio towers sink	Northern Plateau	Closed Depression
Haputo sink 1	Northern Plateau	Closed Depression
Haputo sink 2	Northern Plateau	Closed Depression
Haputo sink 3	Northern Plateau	Closed Depression
Haputo sink 4	Northern Plateau	Closed Depression
Haputo sink 5	Northern Plateau	Closed Depression
Haputo sink 6	Northern Plateau	Closed Depression
Haputo Skylight Sea Cave	Northern Plateau	Sea Cave
Harmon annex depression 1	Northern Plateau	Closed Depression
Harmon annex depression 2	Northern Plateau	Closed Depression
Harmon flea market sink	Northern Plateau	Closed Depression
Harmon sink (a)	Northern Plateau	Closed Depression
Harmon sink (b)	Northern Plateau	Closed Depression
Harmon sink (c)	Northern Plateau	Closed Depression
Harmon Sink Shafts	Northern Plateau	Pit Cave
Hawaiian Rock quarry (a)	Northern Plateau	Closed Depression
Hawaiian Rock quarry (b)	Northern Plateau	Closed Depression
Hawaiian Rock Quarry Beach Spring	Northern Plateau	Discharge Feature
Hawaiian Rock Quarry Cave	Northern Plateau	Abandoned Stream Cave

Table 19 (Continued)

Karst Feature Name	Province	Karst Feature Type
Hawaiian sink 1	Northern Plateau	Closed Depression
Hawaiian sink 2	Northern Plateau	Closed Depression
Haya Pagat Cave	Northern Plateau	Flank Margin Cave
Hilaan Water Fracture	Northern Plateau	Unknown Origin
Hilaan1	Northern Plateau	Discharge Feature
Hilaan2	Northern Plateau	Discharge Feature
Hilaan3	Northern Plateau	Discharge Feature
Hilton	Northern Plateau	Discharge Feature
Hoyo Matugan	Southern Mountain Range	Pit Cave
Hoyu Fena	Southern Interior Basin	Pit Cave
Hoyu Sabana Lamlam	Southern Mountain Range	Pit Cave
Hyatt	Northern Plateau	Discharge Feature
Iates Point Cliff Cave	Northern Plateau	Flank Margin Cave
Ibaba Cave	Southern Interior Basin	Unknown Origin
Interesting Cave	Northern Plateau	Stream Cave
Interesting sink	Northern Plateau	Closed Depression
Ipapao depression 1	Northern Plateau	Closed Depression
Ipapao depression 2	Northern Plateau	Closed Depression
Ipapao ponding basin	Northern Plateau	Closed Depression
Ito and Minagawa sink	Southern Coast	Banana Hole
Janum Area Sea Caves	Northern Plateau	Sea Cave
Janum Beach Cave	Northern Plateau	Flank Margin Cave
Janum Cave	Northern Plateau	Flank Margin Cave
Janum Contact Small Caves	Northern Plateau	Unknown Origin
Janum Spring	Northern Plateau	Discharge Feature
Janum Spring Cave	Northern Plateau	Stream Cave
Joan's Cave	Northern Plateau	Flank Margin Cave
Joe Quitigua's Water Cave	Northern Plateau	Flank Margin Cave
Kiwi	Northern Plateau	Discharge Feature
Lafac cliff depression 1	Northern Plateau	Closed Depression
Lafac cliff depression 2	Northern Plateau	Closed Depression
Lafac cliff depression 3	Northern Plateau	Closed Depression
Lafac Grotto	Northern Plateau	Flank Margin Cave
Lafac Point Cliff Caves	Northern Plateau	Flank Margin Cave
Lafac Point Sea Caves	Northern Plateau	Sea Cave
Lafac-Anao Collapse 1	Northern Plateau	Unknown Origin
Lafac-Anao Collapse 2	Northern Plateau	Unknown Origin
Lafac-Anao Collapse 3	Northern Plateau	Unknown Origin
Latte Heights depression	Northern Plateau	Closed Depression
Latte Heights ponding basin 1	Northern Plateau	Closed Depression

Table 19 (Continued)

Karst Feature Name	Province	Karst Feature Type
Latte Heights ponding basin 2	Northern Plateau	Closed Depression
Latte Heights ponding basin 3	Northern Plateau	Closed Depression
Liyang Almagosa Gelagu	Southern Mountain Range	Abandoned Stream Cave
Liyang Namu Kanutu	Southern Interior Basin	Abandoned Stream Cave
Lost Pond Shelter Caves	Northern Plateau	Flank Margin Cave
Lost River Cave	Southern Interior Basin	Stream Cave
Lost River Rise Cliff Cave	Southern Interior Basin	Abandoned Stream Cave
Lujuna Collapse 1	Northern Plateau	Unknown Origin
Lujuna Collapse 2	Northern Plateau	Unknown Origin
Lujuna Point Cave	Northern Plateau	Flank Margin Cave
Lujuna point sink	Northern Plateau	Closed Depression
Lujuna-Pagat Notch Cave	Northern Plateau	Unknown Origin
Lunch Fracture	Northern Plateau	Discharge Feature
Lupog depression	Northern Plateau	Closed Depression
Lupog depression	Northern Plateau	Closed Depression
Machanao borrow pit	Northern Plateau	Closed Depression
Maemong Bridge South	Southern Interior Basin	Unknown Origin
Maemong Rise	Southern Interior Basin	Discharge Feature
Maemong River Cave	Southern Interior Basin	Recharge Cave
Maimai dry valley sink	Northern Plateau	Closed Depression
Maina sink	Northern Plateau	Closed Depression
Maina Spring sink	Northern Plateau	Closed Depression
Malojloj depression 1	Southern Coast	Closed Depression
Malojloj depression 2	Southern Coast	Closed Depression
Malojloj depression 4	Southern Coast	Closed Depression
Malojloj depression 5	Southern Coast	Closed Depression
Malojloj depression 6	Southern Coast	Closed Depression
Malojloj depression 7	Southern Coast	Closed Depression
Malojloj landfill	Southern Coast	Closed Depression
Manengon sink	Southern Coast	Closed Depression
Mang. Golf Course Fracture Cave	Northern Plateau	Mixing-zone Fracture Cave
Marbo Cave	Northern Plateau	Flank Margin Cave
Marbo pumping station depression	Northern Plateau	Closed Depression
Marine Lab Beach Cave	Northern Plateau	Flank Margin Cave
Mata Cave	Southern Coast	Flank Margin Cave
Mataguac big depression 1	Northern Plateau	Closed Depression
Mataguac big depression 2	Northern Plateau	Closed Depression
Mataguac depression 1	Northern Plateau	Closed Depression
Mataguac depression 2	Northern Plateau	Closed Depression
Mataguac depression 3	Northern Plateau	Closed Depression

Table 19 (Continued)

Karst Feature Name	Province	Karst Feature Type
Mataguac Hill East sink	Northern Plateau	Closed Depression
Mataguac Hill North sink	Northern Plateau	Closed Depression
Mataguac Hill South sink	Northern Plateau	Closed Depression
Mataguac Hill West sink	Northern Plateau	Closed Depression
Mataguac Mud Cave	Northern Plateau	Stream Cave
Mataguac Spring Cave	Northern Plateau	Discharge Feature
Mataguac spring sink	Northern Plateau	Closed Depression
Matala Caves	Southern Coast	Flank Margin Cave
Mati Cliff Pit Cave Complex	Northern Plateau	Pit Cave
Mati point depression	Northern Plateau	Closed Depression
Mati Point High Cliff Cave	Northern Plateau	Flank Margin Cave
Mati Point Sea Caves	Northern Plateau	Sea Cave
Matt's Cave	Northern Plateau	Flank Margin Cave
MDA Cave (Haputo)	Northern Plateau	Unknown Origin
Meamong Bridge North	Southern Interior Basin	Unknown Origin
Mecheche depression	Northern Plateau	Closed Depression
Menpachi	Northern Plateau	Mixing-zone Fracture Cave
Mergagan cliff depression	Northern Plateau	Closed Depression
Mergagan Point Cave	Northern Plateau	Flank Margin Cave
Mergagan Point Notches	Northern Plateau	Flank Margin Cave
Mt Barrigada borrow pit	Northern Plateau	Closed Depression
Mt Santa Rosa quarry 1	Northern Plateau	Closed Depression
Mt Santa Rosa quarry 2	Northern Plateau	Closed Depression
Mt. Almagosa Caves	Southern Mountain Range	Abandoned Stream Cave
Mt. Alutom Cave	Southern Mountain Range	Unknown Origin
Mt. Barrigada Pit	Northern Plateau	Pit Cave
Mt. Santa Rosa Cave	Northern Plateau	Closed Depression
Mt. Santa Rosa eastern sink	Northern Plateau	Closed Depression
Mt. Santa Rosa ponding basin	Northern Plateau	Closed Depression
Mt. Santa Rosa spring sink	Northern Plateau	Closed Depression
Navy golf course depression 1	Northern Plateau	Closed Depression
Navy golf course depression 2	Northern Plateau	Closed Depression
Navy golf course depression 3	Northern Plateau	Closed Depression
Navy golf course depression 4	Northern Plateau	Closed Depression
Nicole's Spring	Northern Plateau	Discharge Feature
Nimitz Hill Cave	Southern Mountain Range	Unknown Origin
Nimitz Hill depression 1	Southern Mountain Range	Closed Depression
Nimitz Hill depression 2	Southern Mountain Range	Closed Depression
No Can	Northern Plateau	Mixing-zone Fracture Cave
North Catalina Beach Caves	Northern Plateau	Flank Margin Cave

Table 19 (Continued)

Karst Feature Name	Province	Karst Feature Type
North Haputo	Northern Plateau	Discharge Feature
North Mataguac Cave	Northern Plateau	Stream Cave
Notre Dame School Caves	Southern Coast	Flank Margin Cave
NW field borrow pit 1	Northern Plateau	Closed Depression
NW field borrow pit 2	Northern Plateau	Closed Depression
NW field borrow pit 3	Northern Plateau	Closed Depression
NW field borrow pit 4	Northern Plateau	Closed Depression
NW field depression	Northern Plateau	Closed Depression
NW field depression 2	Northern Plateau	Closed Depression
NW field depression 3	Northern Plateau	Closed Depression
NW field depression 4	Northern Plateau	Closed Depression
NW field depression 5	Northern Plateau	Closed Depression
Oca borrow pit	Northern Plateau	Closed Depression
Ocean View	Northern Plateau	Discharge Feature
Okura1	Northern Plateau	Discharge Feature
Okura2	Northern Plateau	Discharge Feature
Okura3	Northern Plateau	Discharge Feature
Okura4	Northern Plateau	Discharge Feature
Ordot depression	Northern Plateau	Closed Depression
Ordot small depression	Northern Plateau	Closed Depression
Orote Channel Cave	Southern Coast	Flank Margin Cave
Orote Cliff Cave	Southern Coast	Flank Margin Cave
Orote depression 1	Southern Coast	Closed Depression
Orote depression 2	Southern Coast	Closed Depression
Orote depression 3	Southern Coast	Closed Depression
Orote depression 4	Southern Coast	Closed Depression
Orote Sagan Basula Cave	Southern Coast	Unknown Origin
Orote Window	Southern Coast	Flank Margin Cave
Orotte Grottos (north)	Southern Coast	Flank Margin Cave
Orotte Grottos (south)	Southern Coast	Flank Margin Cave
Pac Star	Northern Plateau	Discharge Feature
Pagat Cave	Northern Plateau	Flank Margin Cave
Pagat Collapse	Northern Plateau	Unknown Origin
Pagat Point Sea Cave	Northern Plateau	Sea Cave
Pagat Point Shelter Cave	Northern Plateau	Flank Margin Cave
Pagat Sea Arch	Northern Plateau	Unknown Origin
Pago Bay depression	Northern Plateau	Closed Depression
Pago Bay dry valley sink	Northern Plateau	Closed Depression
Pago River tributary sink	Northern Plateau	Closed Depression
Palasao Cave	Southern Mountain Range	Contact Cave

Table 19 (Continued)

Karst Feature Name	Province	Karst Feature Type
Park	Northern Plateau	Discharge Feature
Pati Point 3 Fissures	Northern Plateau	Unknown Origin
Pati Point 3 Sea Caves	Northern Plateau	Sea Cave
Patinian	Northern Plateau	Discharge Feature
Perez Brothers quarry (a-b)	Northern Plateau	Closed Depression
Perez Brothers quarry (c)	Northern Plateau	Closed Depression
Piggy Cave	Northern Plateau	Contact Cave
Pinate main depression	Northern Plateau	Closed Depression
Pinate sink 1	Northern Plateau	Closed Depression
Pinate sink 2	Northern Plateau	Closed Depression
Pinate sink 3	Northern Plateau	Closed Depression
Pinate sink 4	Northern Plateau	Closed Depression
Pinnacle Cave	Southern Mountain Range	Unknown Origin
Pit Near Lost River Rise	Southern Interior Basin	Pit Cave
Potts Junction depression	Northern Plateau	Closed Depression
Potts Junction ponding basin 1	Northern Plateau	Closed Depression
Potts Junction ponding basin 4	Northern Plateau	Closed Depression
Potts Junction ponding basins 2-3	Northern Plateau	Closed Depression
Public works quarry	Northern Plateau	Closed Depression
Pugua Point Cave	Northern Plateau	Flank Margin Cave
Pugua point depression	Northern Plateau	Closed Depression
Pugua Point Sea Caves	Northern Plateau	Sea Cave
Pulatar dry valley sinks	Northern Plateau	Closed Depression
Pulatar sink	Northern Plateau	Closed Depression
Randall	Northern Plateau	Discharge Feature
Ritidian Beach Cave	Northern Plateau	Flank Margin Cave
Ritidian Cave	Northern Plateau	Flank Margin Cave
Ritidian cliff depression 1	Northern Plateau	Closed Depression
Ritidian cliff depression 2	Northern Plateau	Closed Depression
Ritidian cliff depression 3	Northern Plateau	Closed Depression
Ritidian Double Arch	Northern Plateau	Flank Margin Cave
Ritidian Gate Cave	Northern Plateau	Flank Margin Cave
Ritidian Pictograph Cave	Northern Plateau	Flank Margin Cave
Ritidian Spring	Northern Plateau	Discharge Feature
Ritidian View Cave	Northern Plateau	Flank Margin Cave
Sabanan Pagat sink	Northern Plateau	Closed Depression
Scott's Fracture	Northern Plateau	Mixing-zone Fracture Cave
Scout's Beach Seeps	Northern Plateau	Discharge Feature
Sinajana sink 1	Northern Plateau	Closed Depression
Sinajana sink 2	Northern Plateau	Closed Depression

Table 19 (Continued)

Karst Feature Name	Province	Karst Feature Type
Sinajana sink 3	Northern Plateau	Closed Depression
Small Cave South of Latte	Northern Plateau	Flank Margin Cave
Small Cave South of Pati	Northern Plateau	Flank Margin Cave
South Catalina Beach Caves	Northern Plateau	Flank Margin Cave
South Haputo	Northern Plateau	Discharge Feature
Submarine vents	Northern Plateau	Discharge Feature
Submarine vents	Northern Plateau	Discharge Feature
Submarine vents	Northern Plateau	Discharge Feature
Suma Cave	Southern Coast	Unknown Origin
Swimming Hole	Northern Plateau	Discharge Feature
Taga'chang Beach Pit	Southern Coast	Pit Cave
Tagua Cave	Northern Plateau	Flank Margin Cave
Tagua cliff depression	Northern Plateau	Closed Depression
Tagua Point Seeps	Northern Plateau	Discharge Feature
Talofofo Bay Overhang	Southern Coast	Flank Margin Cave
Talofofo Cave #1	Southern Coast	Abandoned Stream Cave
Talofofo Cave #2	Southern Coast	Abandoned Stream Cave
Talofofo Cave #3	Southern Coast	Abandoned Stream Cave
Talofofo Cave #4	Southern Coast	Abandoned Stream Cave
Talofofo Cave #5	Southern Coast	Abandoned Stream Cave
Talofofo Cave #6	Southern Coast	Abandoned Stream Cave
Talofofo depression 1	Southern Coast	Closed Depression
Talofofo depression 2	Southern Coast	Closed Depression
Talofofo depression 3	Southern Coast	Closed Depression
Talofofo depression 4	Southern Coast	Closed Depression
Talofofo depression 5	Southern Coast	Closed Depression
Talofofo depression 6	Southern Coast	Closed Depression
Talofofo depression 7	Southern Coast	Closed Depression
Talofofo golf course sink 1	Southern Coast	Closed Depression
Talofofo golf course sink 2	Southern Coast	Closed Depression
Talofofo Pit Cave	Southern Coast	Pit Cave
Tamuning school borrow pit	Northern Plateau	Closed Depression
Tanguisson1a	Northern Plateau	Discharge Feature
Tanguisson1b	Northern Plateau	Discharge Feature
Tanguisson2a	Northern Plateau	Discharge Feature
Tanguisson2b	Northern Plateau	Discharge Feature
Tanguisson3a	Northern Plateau	Discharge Feature
Tanguisson3b	Northern Plateau	Discharge Feature
Tanguisson3c	Northern Plateau	Discharge Feature
Tarague beach road depression	Northern Plateau	Closed Depression

Table 19 (Continued)

Karst Feature Name	Province	Karst Feature Type
Tarague Beach View Cave	Northern Plateau	Flank Margin Cave
Tarague Cave	Northern Plateau	Flank Margin Cave
Tarague cliff depression 1	Northern Plateau	Closed Depression
Tarague cliff depression 2	Northern Plateau	Closed Depression
Tarague Cliff Pit	Northern Plateau	Pit Cave
Tarague Copra Cave	Northern Plateau	Flank Margin Cave
Tarague East Cliff Cave	Northern Plateau	Flank Margin Cave
Tarague embayment borrow pit	Northern Plateau	Closed Depression
Tarague Seeps	Northern Plateau	Discharge Feature
Tarague Well #5	Northern Plateau	Flank Margin Cave
Tarague West Cliff Cave	Northern Plateau	Flank Margin Cave
Tipalao Cave	Southern Coast	Flank Margin Cave
Tipoco Island Arch	Southern Coast	Unknown Origin
Togcha depression	Southern Coast	Closed Depression
Tolae Yu'us Cave	Southern Interior Basin	Recharge Cave
Tolae Yu'us Kinahulo'guan	Southern Interior Basin	Discharge Feature
Tres Botsas	Southern Coast	Flank Margin Cave
Turkey Rock	Northern Plateau	Discharge Feature
Tweed's Cave	Northern Plateau	Non-Karst
Two Lovers' Pit Cave	Northern Plateau	Pit Cave
Ukudu depression	Northern Plateau	Closed Depression
Ulua Cave	Northern Plateau	Discharge Feature
Uruno cliff burrow pit 1	Northern Plateau	Closed Depression
Uruno cliff burrow pit 2	Northern Plateau	Closed Depression
Uruno Point Cave	Northern Plateau	Flank Margin Cave
Uruno Point Small Cave 1	Northern Plateau	Flank Margin Cave
Uruno Point Small Cave 2	Northern Plateau	Flank Margin Cave
US Weather Bureau depression 1	Northern Plateau	Closed Depression
US Weather Bureau depression 2	Northern Plateau	Closed Depression
Virgin Cave	Northern Plateau	Stream Cave
Virgin Mary Shelter Cave	Southern Mountain Range	Flank Margin Cave
War dog cemetary sink	Northern Plateau	Closed Depression
Westin	Northern Plateau	Discharge Feature
Wet Willies	Northern Plateau	Discharge Feature
Wettengel Junction depression	Northern Plateau	Closed Depression
Window Rock	Southern Coast	Unknown Origin
Yigo depression 1	Northern Plateau	Closed Depression
Yigo depression 2	Northern Plateau	Closed Depression
Yigo ponding basin 1	Northern Plateau	Closed Depression
Yigo ponding basin 2	Northern Plateau	Closed Depression
Yigo ponding basin 3	Northern Plateau	Closed Depression

Table 19 (Continued)

Karst Feature Name	Province	Karst Feature Type
Yigo School quarry	Northern Plateau	Closed Depression
Yigo Sink	Northern Plateau	Closed Depression
Ylig Bay Cave	Southern Coast	Unknown Origin
Yona depression 1	Southern Coast	Closed Depression
Yona depression 2	Southern Coast	Closed Depression
Ypao Cave	Northern Plateau	Flank Margin Cave
Ypao Stalactite Cave	Northern Plateau	Flank Margin Cave
Ysengson depression 6	Northern Plateau	Closed Depression
Ysengson depression 7	Northern Plateau	Closed Depression
Ysengsong depression 1	Northern Plateau	Closed Depression
Ysengsong depression 2	Northern Plateau	Closed Depression
Ysengsong depression 3	Northern Plateau	Closed Depression
Ysengsong depression 4	Northern Plateau	Closed Depression
Ysengsong long depression	Northern Plateau	Closed Depression

APPENDIX C

CAVE AND KARST INVENTORY OF ROTA

MAPS AND DESCRIPTIONS

The following data is used with permission from Keel (2005). The data has been reorganized from its original alphabetical order to being organized alphabetically by province and karst feature type. The only changes made were minor spelling and grammatical fixes and the changes summarized in Table 4. Table 20 shows the caves of Rota in alphabetical order, Table 21 shows the caves of Rota alphabetically within cave type, and Table 22 shows them alphabetically within the province. For ease of use, all tables include the page number that the cave's map and description starts.

Table 20: Table of the caves of Rota in alphabetical order

Cave Name	Cave Type	Province	Page Number
Agrippa Cave	Flank Margin Cave	Sabana	378
Alaguan Bay Cave	Flank Margin Cave	Sabana	379
Alaguan Cave	Flank Margin Cave	Sabana	380
Alaguan Feature A2	Flank Margin Cave	Sabana	381
Alaguan Feature A3	Flank Margin Cave	Sabana	382
Alaguan Sea Cave A1	Sea Cave	Sabana	443
Alapin Two	Flank Margin Cave	Sabana	383
Al-Su Cave	Mixing-zone Fracture Cave	Sabana	423
Arch Cave	Flank Margin Cave	Sabana	384
Arrowhead Cave	Mixing-zone Fracture Cave	Sinapolo	471
As Matan Cave	Flank Margin Cave	Sabana	385
As Onan Spring	Contact Cave	Sabana	348
Banyan Complex	Fissure Cave	Sinapolo	468
Barbed Wire Cave	Flank Margin Cave	Sabana	387
Bare Foot Cave	Sea Cave	Sinapolo	451
Basement Cave	Mixing-zone Fracture Cave	Sinapolo	472
Bay Cave Remnant	Flank Margin Cave	Sabana	388
Bee Cave	Fissure Cave	Taipingot	497
Big Fern Cave	Fissure Cave	Sabana	360
Birthday Cave	Mixing-zone Fracture Cave	Sinapolo	473
Bitsy Cave	Fissure Cave	Sabana	361
Black Cobble Cave	Contact Cave	Sabana	349
Bonus Cave	Mixing-zone Fracture Cave	Sinapolo	474
Breadfruit Cave	Flank Margin Cave	Sabana	389
Breccia Cave	Flank Margin Cave	Sabana	390
Breeze Cave	Fissure Cave	Sabana	362
Broken Mortar Cave	Flank Margin Cave	Taipingot	498
Buffalo Cave	Flank Margin Cave	Sinapolo	452
Canyon Cave	Mixing-zone Fracture Cave	Sabana	424
Christmas Cave	Flank Margin Cave	Sabana	393
Comet Cave	Flank Margin Cave	Sabana	393
Compact Cave	Flank Margin Cave	Sabana	394
Crab Hunter Cave	Flank Margin Cave	Sabana	396
Cupid Cave	Flank Margin Cave	Sabana	397
Dancer Cave	Flank Margin Cave	Sabana	398
Dasher Cave	Flank Margin Cave	Sabana	399
Deer Cave	Mixing-zone Fracture Cave	Sabana	425
Delia Cave	Mixing-zone Fracture Cave	Sinapolo	475
Diagonal Fissure Cave	Fissure Cave	Sabana	364
Discus Cave	Contact Cave	Sabana	351
Double Cave	Sea Cave	Sabana	444

Table 20 (Continued)

Cave Name	Cave Type	Province	Page Number
Double Decker Cave	Flank Margin Cave	Sabana	400
Even Smaller Cave	Fissure Cave	Sinapolo	469
Exception Cave	Flank Margin Cave	Sinapolo	454
Fall In Cave	Fissure Cave	Sabana	365
Fisherman Cave	Flank Margin Cave	Sinapolo	455
Fissure City Cave	Fissure Cave	Sabana	367
Flange Cave	Fissure Cave	Sabana	368
Forked Cave	Mixing-zone Fracture Cave	Sinapolo	476
Four Crosses	Mixing-zone Fracture Cave	Sabana	426
Gagani Cave	Contact Cave	Sabana	351
Grand Stand Cave	Flank Margin Cave	Sabana	401
Green Fissure Cave	Fissure Cave	Sabana	369
Hammer Cave	Mixing-zone Fracture Cave	Sabana	427
Hang Out Cave	Mixing-zone Fracture Cave	Sabana	428
Henry Fissure Cave	Fissure Cave	Sabana	370
Honey Comb Cave	Mixing-zone Fracture Cave	Sinapolo	477
Honey Eater Cave	Mixing-zone Fracture Cave	Sinapolo	478
Hourglass Cave	Flank Margin Cave	Sinapolo	456
Husky Cave	Flank Margin Cave	Sabana	402
I'm Your Cistern Cave	Flank Margin Cave	Sabana	403
Incidental Cave	Mixing-zone Fracture Cave	Sabana	429
Itsey Cave	Flank Margin Cave	Sabana	404
Jug Handle Fissure	Fissure Cave	Sabana	371
Kaigun 223 Japanese Command Post	Man Made Feature	Sabana	448
Knuckle Bone Cave	Mixing-zone Fracture Cave	Sinapolo	479
Letterman Cave	Mixing-zone Fracture Cave	Sinapolo	481
Little S Cave	Mixing-zone Fracture Cave	Sinapolo	482
Liyang Alapin	Mixing-zone Fracture Cave	Sabana	430
Liyang Apaka’	Mixing-zone Fracture Cave	Sinapolo	483
Liyang Ayuyu	Flank Margin Cave	Sinapolo	457
Liyang Botazon	Mixing-zone Fracture Cave	Sinapolo	485
Liyang Chenchon	Flank Margin Cave	Sinapolo	458
Liyang Finta	Mixing-zone Fracture Cave	Sinapolo	487
Liyang Ganas and Nanonk Kastiyu	Mixing-zone Fracture Cave	Sabana	432
Liyang Lu’ao	Mixing-zone Fracture Cave	Sinapolo	488
Liyang Matan	Mixing-zone Fracture Cave	Sinapolo	489
Liyang Neni	Mixing-zone Fracture Cave	Sinapolo	491
Liyang Paluma	Mixing-zone Fracture Cave	Sinapolo	492
Liyang Perseverance	Mixing-zone Fracture Cave	Sabana	433
Liyang Siete	Mixing-zone Fracture Cave	Sinapolo	493
Liyang Tonga (Taga)	Mixing-zone Fracture Cave	Sabana	436

Table 20 (Continued)

Cave Name	Cave Type	Province	Page Number
Mendiola Cave	Unknown Origin	Sabana	446
Mermaid Cave	Flank Margin Cave	Sinapolo	459
Misplaced Cave	Flank Margin Cave	Sabana	405
Monkey Cave	Flank Margin Cave	Sinapolo	460
Mosquito Fissure Cave	Fissure Cave	Sabana	372
North Side Trickle Cave	Contact Cave	Sabana	353
Not Much Cave	Fissure Cave	Sinapolo	470
One Shot Cave	Fissure Cave	Sabana	373
Paupau Sea Cave	Sea Cave	Taipingot	499
Peace Memorial Tunnels	Man Made Feature	Sabana	449
Picnic Cave	Flank Margin Cave	Sabana	406
Pictograph Cave	Mixing-zone Fracture Cave	Sinapolo	494
Pie Cave	Flank Margin Cave	Sabana	408
Pona North Sea Cave	Sea Cave	Sabana	445
Prancer Cave	Flank Margin Cave	Sabana	408
Rainy Day Cave	Mixing-zone Fracture Cave	Sabana	438
Reservoir Cave	Contact Cave	Sabana	354
Reyes Flank Margin Cave Complex	Flank Margin Cave	Sinapolo	461
Ripple Cave	Flank Margin Cave	Sinapolo	462
Rock Pile Cave	Mixing-zone Fracture Cave	Sabana	438
Root Wall Cave	Fissure Cave	Sabana	374
Rota Rooter Cave	Contact Cave	Sabana	356
Sagua Cave Complex	Flank Margin Cave	Sabana	410
Saguita Cave	Flank Margin Cave	Sabana	414
Seastack Cave	Flank Margin Cave	Sabana	415
Second Chance Cave	Mixing-zone Fracture Cave	Sabana	439
Shoo Fly Cave	Flank Margin Cave	Sabana	416
Slab Cave	Fissure Cave	Sinapolo	470
Stacked Wall Cave	Flank Margin Cave	Sabana	417
Summit Cave	Contact Cave	Sabana	357
Surge Cave	Flank Margin Cave	Sinapolo	463
Taisacan Museum (Antigo) Cave	Mixing-zone Fracture Cave	Sabana	442
Tea Kettle Fissure	Fissure Cave	Sabana	375
The Swimming Hole	Flank Margin Cave	Sinapolo	465
Tree Top Cave	Flank Margin Cave	Sabana	418
Truck Rig Pit	Pit Cave	Sinapolo	495
Village View Cave	Fissure Cave	Sabana	376
Vixen Cave	Flank Margin Cave	Sabana	419
Water Cave (Matan Hanum)	Flank Margin Cave	Sabana	420

Table 21: The caves of Rota alphabetically by cave type

Cave Name	Cave Type	Province	Page Number
As Onan Spring	Contact Cave	Sabana	348
Black Cobble Cave	Contact Cave	Sabana	349
Discus Cave	Contact Cave	Sabana	351
Gagani Cave	Contact Cave	Sabana	351
North Side Trickle Cave	Contact Cave	Sabana	353
Reservoir Cave	Contact Cave	Sabana	354
Rota Rooter Cave	Contact Cave	Sabana	356
Summit Cave	Contact Cave	Sabana	357
Banyan Complex	Fissure Cave	Sinapolo	468
Bee Cave	Fissure Cave	Taipingot	497
Big Fern Cave	Fissure Cave	Sabana	360
Bitsy Cave	Fissure Cave	Sabana	361
Breeze Cave	Fissure Cave	Sabana	362
Diagonal Fissure Cave	Fissure Cave	Sabana	364
Even Smaller Cave	Fissure Cave	Sinapolo	469
Fall In Cave	Fissure Cave	Sabana	365
Fissure City Cave	Fissure Cave	Sabana	367
Flange Cave	Fissure Cave	Sabana	368
Green Fissure Cave	Fissure Cave	Sabana	369
Henry Fissure Cave	Fissure Cave	Sabana	370
Jug Handle Fissure	Fissure Cave	Sabana	371
Mosquito Fissure Cave	Fissure Cave	Sabana	372
Not Much Cave	Fissure Cave	Sinapolo	470
One Shot Cave	Fissure Cave	Sabana	373
Root Wall Cave	Fissure Cave	Sabana	374
Slab Cave	Fissure Cave	Sinapolo	470
Tea Kettle Fissure	Fissure Cave	Sabana	375
Village View Cave	Fissure Cave	Sabana	376
Agrippa Cave	Flank Margin Cave	Sabana	378
Alaguan Bay Cave	Flank Margin Cave	Sabana	379
Alaguan Cave	Flank Margin Cave	Sabana	380
Alaguan Feature A2	Flank Margin Cave	Sabana	381
Alaguan Feature A3	Flank Margin Cave	Sabana	382
Alapin Two	Flank Margin Cave	Sabana	383
Arch Cave	Flank Margin Cave	Sabana	384
As Matan Cave	Flank Margin Cave	Sabana	385
Barbed Wire Cave	Flank Margin Cave	Sabana	387
Bay Cave Remnant	Flank Margin Cave	Sabana	388
Breadfruit Cave	Flank Margin Cave	Sabana	389
Breccia Cave	Flank Margin Cave	Sabana	390
Broken Mortar Cave	Flank Margin Cave	Taipingot	498

Table 21 (Continued)

Cave Name	Cave Type	Province	Page Number
Buffalo Cave	Flank Margin Cave	Sinapolo	452
Christmas Cave	Flank Margin Cave	Sabana	393
Comet Cave	Flank Margin Cave	Sabana	393
Compact Cave	Flank Margin Cave	Sabana	394
Crab Hunter Cave	Flank Margin Cave	Sabana	396
Cupid Cave	Flank Margin Cave	Sabana	397
Dancer Cave	Flank Margin Cave	Sabana	398
Dasher Cave	Flank Margin Cave	Sabana	399
Double Decker Cave	Flank Margin Cave	Sabana	400
Exception Cave	Flank Margin Cave	Sinapolo	454
Fisherman Cave	Flank Margin Cave	Sinapolo	455
Grand Stand Cave	Flank Margin Cave	Sabana	401
Hourglass Cave	Flank Margin Cave	Sinapolo	456
Husky Cave	Flank Margin Cave	Sabana	402
I'm Your Cistern Cave	Flank Margin Cave	Sabana	403
Itsey Cave	Flank Margin Cave	Sabana	404
Liyang Ayuyu	Flank Margin Cave	Sinapolo	457
Liyang Chenchon	Flank Margin Cave	Sinapolo	458
Mermaid Cave	Flank Margin Cave	Sinapolo	459
Misplaced Cave	Flank Margin Cave	Sabana	405
Monkey Cave	Flank Margin Cave	Sinapolo	460
Picnic Cave	Flank Margin Cave	Sabana	406
Pie Cave	Flank Margin Cave	Sabana	408
Prancer Cave	Flank Margin Cave	Sabana	408
Reyes Flank Margin Cave Complex	Flank Margin Cave	Sinapolo	461
Ripple Cave	Flank Margin Cave	Sinapolo	462
Sagua Cave Complex	Flank Margin Cave	Sabana	410
Saguita Cave	Flank Margin Cave	Sabana	414
Seastack Cave	Flank Margin Cave	Sabana	415
Shoo Fly Cave	Flank Margin Cave	Sabana	416
Stacked Wall Cave	Flank Margin Cave	Sabana	417
Surge Cave	Flank Margin Cave	Sinapolo	463
The Swimming Hole	Flank Margin Cave	Sinapolo	465
Tree Top Cave	Flank Margin Cave	Sabana	418
Vixen Cave	Flank Margin Cave	Sabana	419
Water Cave (Matan Hanum)	Flank Margin Cave	Sabana	420
Kaigun 223 Japanese Command Post	Man Made Feature	Sabana	448
Peace Memorial Tunnels	Man Made Feature	Sabana	449
Al-Su Cave	Mixing-zone Fracture Cave	Sabana	423
Arrowhead Cave	Mixing-zone Fracture Cave	Sinapolo	471
Basement Cave	Mixing-zone Fracture Cave	Sinapolo	472

Table 21 (Continued)

Cave Name	Cave Type	Province	Page Number
Birthday Cave	Mixing-zone Fracture Cave	Sinapolo	473
Bonus Cave	Mixing-zone Fracture Cave	Sinapolo	474
Canyon Cave	Mixing-zone Fracture Cave	Sabana	424
Deer Cave	Mixing-zone Fracture Cave	Sabana	425
Delia Cave	Mixing-zone Fracture Cave	Sinapolo	475
Forked Cave	Mixing-zone Fracture Cave	Sinapolo	476
Four Crosses	Mixing-zone Fracture Cave	Sabana	426
Hammer Cave	Mixing-zone Fracture Cave	Sabana	427
Hang Out Cave	Mixing-zone Fracture Cave	Sabana	428
Honey Comb Cave	Mixing-zone Fracture Cave	Sinapolo	477
Honey Eater Cave	Mixing-zone Fracture Cave	Sinapolo	478
Incidental Cave	Mixing-zone Fracture Cave	Sabana	429
Knuckle Bone Cave	Mixing-zone Fracture Cave	Sinapolo	479
Letterman Cave	Mixing-zone Fracture Cave	Sinapolo	481
Little S Cave	Mixing-zone Fracture Cave	Sinapolo	482
Liyang Alapin	Mixing-zone Fracture Cave	Sabana	430
Liyang Apaka’	Mixing-zone Fracture Cave	Sinapolo	483
Liyang Botazon	Mixing-zone Fracture Cave	Sinapolo	485
Liyang Finta	Mixing-zone Fracture Cave	Sinapolo	487
Liyang Ganas and Nanonk Kastiyu	Mixing-zone Fracture Cave	Sabana	432
Liyang Lu’ao	Mixing-zone Fracture Cave	Sinapolo	488
Liyang Matan	Mixing-zone Fracture Cave	Sinapolo	489
Liyang Neni	Mixing-zone Fracture Cave	Sinapolo	491
Liyang Paluma	Mixing-zone Fracture Cave	Sinapolo	492
Liyang Perseverance	Mixing-zone Fracture Cave	Sabana	433
Liyang Siete	Mixing-zone Fracture Cave	Sinapolo	493
Liyang Tonga (Taga)	Mixing-zone Fracture Cave	Sabana	436
Pictograph Cave	Mixing-zone Fracture Cave	Sinapolo	494
Rainy Day Cave	Mixing-zone Fracture Cave	Sabana	438
Rock Pile Cave	Mixing-zone Fracture Cave	Sabana	438
Second Chance Cave	Mixing-zone Fracture Cave	Sabana	439
Taisacan Museum (Antigo) Cave	Mixing-zone Fracture Cave	Sabana	442
Truck Rig Pit	Pit Cave	Sinapolo	495
Alaguan Sea Cave A1	Sea Cave	Sabana	443
Bare Foot Cave	Sea Cave	Sinapolo	451
Double Cave	Sea Cave	Sabana	444
Paupau Sea Cave	Sea Cave	Taipingot	499
Pona North Sea Cave	Sea Cave	Sabana	445
Mendiola Cave	Unknown Origin	Sabana	446

Table 22: The caves of Rota alphabetically by Province

Cave Name	Cave Type	Province	Page Number
Agrippa Cave	Flank Margin Cave	Sabana	378
Alaguan Bay Cave	Flank Margin Cave	Sabana	379
Alaguan Cave	Flank Margin Cave	Sabana	380
Alaguan Feature A2	Flank Margin Cave	Sabana	381
Alaguan Feature A3	Flank Margin Cave	Sabana	382
Alaguan Sea Cave A1	Sea Cave	Sabana	443
Alapin Two	Flank Margin Cave	Sabana	383
Al-Su Cave	Mixing-zone Fracture Cave	Sabana	423
Arch Cave	Flank Margin Cave	Sabana	384
As Matan Cave	Flank Margin Cave	Sabana	385
As Onan Spring	Contact Cave	Sabana	348
Barbed Wire Cave	Flank Margin Cave	Sabana	387
Bay Cave Remnant	Flank Margin Cave	Sabana	388
Big Fern Cave	Fissure Cave	Sabana	360
Bitsy Cave	Fissure Cave	Sabana	361
Black Cobble Cave	Contact Cave	Sabana	349
Breadfruit Cave	Flank Margin Cave	Sabana	389
Breccia Cave	Flank Margin Cave	Sabana	390
Breeze Cave	Fissure Cave	Sabana	362
Canyon Cave	Mixing-zone Fracture Cave	Sabana	424
Christmas Cave	Flank Margin Cave	Sabana	393
Comet Cave	Flank Margin Cave	Sabana	393
Compact Cave	Flank Margin Cave	Sabana	394
Crab Hunter Cave	Flank Margin Cave	Sabana	396
Cupid Cave	Flank Margin Cave	Sabana	397
Dancer Cave	Flank Margin Cave	Sabana	398
Dasher Cave	Flank Margin Cave	Sabana	399
Deer Cave	Mixing-zone Fracture Cave	Sabana	425
Diagonal Fissure Cave	Fissure Cave	Sabana	364
Discus Cave	Contact Cave	Sabana	351
Double Cave	Sea Cave	Sabana	444
Double Decker Cave	Flank Margin Cave	Sabana	400
Fall In Cave	Fissure Cave	Sabana	365
Fissure City Cave	Fissure Cave	Sabana	367
Flange Cave	Fissure Cave	Sabana	368
Four Crosses	Mixing-zone Fracture Cave	Sabana	426
Gagani Cave	Contact Cave	Sabana	351
Grand Stand Cave	Flank Margin Cave	Sabana	401
Green Fissure Cave	Fissure Cave	Sabana	369
Hammer Cave	Mixing-zone Fracture Cave	Sabana	427
Hang Out Cave	Mixing-zone Fracture Cave	Sabana	428

Table 22 (Continued)

Cave Name	Cave Type	Province	Page Number
Henry Fissure Cave	Fissure Cave	Sabana	370
Husky Cave	Flank Margin Cave	Sabana	402
I'm Your Cistern Cave	Flank Margin Cave	Sabana	403
Incidental Cave	Mixing-zone Fracture Cave	Sabana	429
Itsey Cave	Flank Margin Cave	Sabana	404
Jug Handle Fissure	Fissure Cave	Sabana	371
Kaigun 223 Japanese Command Post	Man Made Feature	Sabana	448
Liyang Alapin	Mixing-zone Fracture Cave	Sabana	430
Liyang Ganas and Nanonk Kastiyu	Mixing-zone Fracture Cave	Sabana	432
Liyang Perseverance	Mixing-zone Fracture Cave	Sabana	433
Liyang Tonga (Taga)	Mixing-zone Fracture Cave	Sabana	436
Mendiola Cave	Unknown Origin	Sabana	446
Misplaced Cave	Flank Margin Cave	Sabana	405
Mosquito Fissure Cave	Fissure Cave	Sabana	372
North Side Trickle Cave	Contact Cave	Sabana	353
One Shot Cave	Fissure Cave	Sabana	373
Peace Memorial Tunnels	Man Made Feature	Sabana	449
Picnic Cave	Flank Margin Cave	Sabana	406
Pie Cave	Flank Margin Cave	Sabana	408
Pona North Sea Cave	Sea Cave	Sabana	445
Prancer Cave	Flank Margin Cave	Sabana	408
Rainy Day Cave	Mixing-zone Fracture Cave	Sabana	438
Reservoir Cave	Contact Cave	Sabana	354
Rock Pile Cave	Mixing-zone Fracture Cave	Sabana	438
Root Wall Cave	Fissure Cave	Sabana	374
Rota Rooter Cave	Contact Cave	Sabana	356
Sagua Cave Complex	Flank Margin Cave	Sabana	410
Saguita Cave	Flank Margin Cave	Sabana	414
Seastack Cave	Flank Margin Cave	Sabana	415
Second Chance Cave	Mixing-zone Fracture Cave	Sabana	439
Shoo Fly Cave	Flank Margin Cave	Sabana	416
Stacked Wall Cave	Flank Margin Cave	Sabana	417
Summit Cave	Contact Cave	Sabana	357
Taisacan Museum (Antigo) Cave	Mixing-zone Fracture Cave	Sabana	442
Tea Kettle Fissure	Fissure Cave	Sabana	375
Tree Top Cave	Flank Margin Cave	Sabana	418
Village View Cave	Fissure Cave	Sabana	376
Vixen Cave	Flank Margin Cave	Sabana	419
Water Cave (Matan Hanum)	Flank Margin Cave	Sabana	420
Arrowhead Cave	Mixing-zone Fracture Cave	Sinapolo	471
Banyan Complex	Fissure Cave	Sinapolo	468

Table 22 (Continued)

Cave Name	Cave Type	Province	Page Number
Bare Foot Cave	Sea Cave	Sinapolo	451
Basement Cave	Mixing-zone Fracture Cave	Sinapolo	472
Birthday Cave	Mixing-zone Fracture Cave	Sinapolo	473
Bonus Cave	Mixing-zone Fracture Cave	Sinapolo	474
Buffalo Cave	Flank Margin Cave	Sinapolo	452
Delia Cave	Mixing-zone Fracture Cave	Sinapolo	475
Even Smaller Cave	Fissure Cave	Sinapolo	469
Exception Cave	Flank Margin Cave	Sinapolo	454
Fisherman Cave	Flank Margin Cave	Sinapolo	455
Forked Cave	Mixing-zone Fracture Cave	Sinapolo	476
Honey Comb Cave	Mixing-zone Fracture Cave	Sinapolo	477
Honey Eater Cave	Mixing-zone Fracture Cave	Sinapolo	478
Hourglass Cave	Flank Margin Cave	Sinapolo	456
Knuckle Bone Cave	Mixing-zone Fracture Cave	Sinapolo	479
Letterman Cave	Mixing-zone Fracture Cave	Sinapolo	481
Little S Cave	Mixing-zone Fracture Cave	Sinapolo	482
Liyang Apaka’	Mixing-zone Fracture Cave	Sinapolo	483
Liyang Ayuyu	Flank Margin Cave	Sinapolo	457
Liyang Botazon	Mixing-zone Fracture Cave	Sinapolo	485
Liyang Chenchon	Flank Margin Cave	Sinapolo	458
Liyang Finta	Mixing-zone Fracture Cave	Sinapolo	487
Liyang Lu’ao	Mixing-zone Fracture Cave	Sinapolo	488
Liyang Matan	Mixing-zone Fracture Cave	Sinapolo	489
Liyang Neni	Mixing-zone Fracture Cave	Sinapolo	491
Liyang Paluma	Mixing-zone Fracture Cave	Sinapolo	492
Liyang Siete	Mixing-zone Fracture Cave	Sinapolo	493
Mermaid Cave	Flank Margin Cave	Sinapolo	459
Monkey Cave	Flank Margin Cave	Sinapolo	460
Not Much Cave	Fissure Cave	Sinapolo	470
Pictograph Cave	Mixing-zone Fracture Cave	Sinapolo	494
Reyes Flank Margin Cave Complex	Flank Margin Cave	Sinapolo	461
Ripple Cave	Flank Margin Cave	Sinapolo	462
Slab Cave	Fissure Cave	Sinapolo	470
Surge Cave	Flank Margin Cave	Sinapolo	463
The Swimming Hole	Flank Margin Cave	Sinapolo	465
Truck Rig Pit	Pit Cave	Sinapolo	495
Bee Cave	Fissure Cave	Taipingot	497
Broken Mortar Cave	Flank Margin Cave	Taipingot	498
Paupau Sea Cave	Sea Cave	Taipingot	499

SABANA

Contact Caves

As Onan Spring

As Onan Spring, located at about 350 m elevation on the east end of the *Talakhaya*, is used as a source for municipal water that is pipe to the *Sinapalo* region of Rota. This feature is a series of springs at the limestone/volcanic contact, modified with small concrete catchments and pipes to collect the water and surrounded by a chain link fence on the down slope side. The limestone overhangs the igneous rocks for about 50 m along the cliff face creating a shelter cave 3-4 m wide and a maximum of 3 m high. At the individual springs, small passages have developed along the contact that penetrate no more than 1-2 m beyond the back wall in most cases. The longest penetrates about 8 m before becoming impassable.

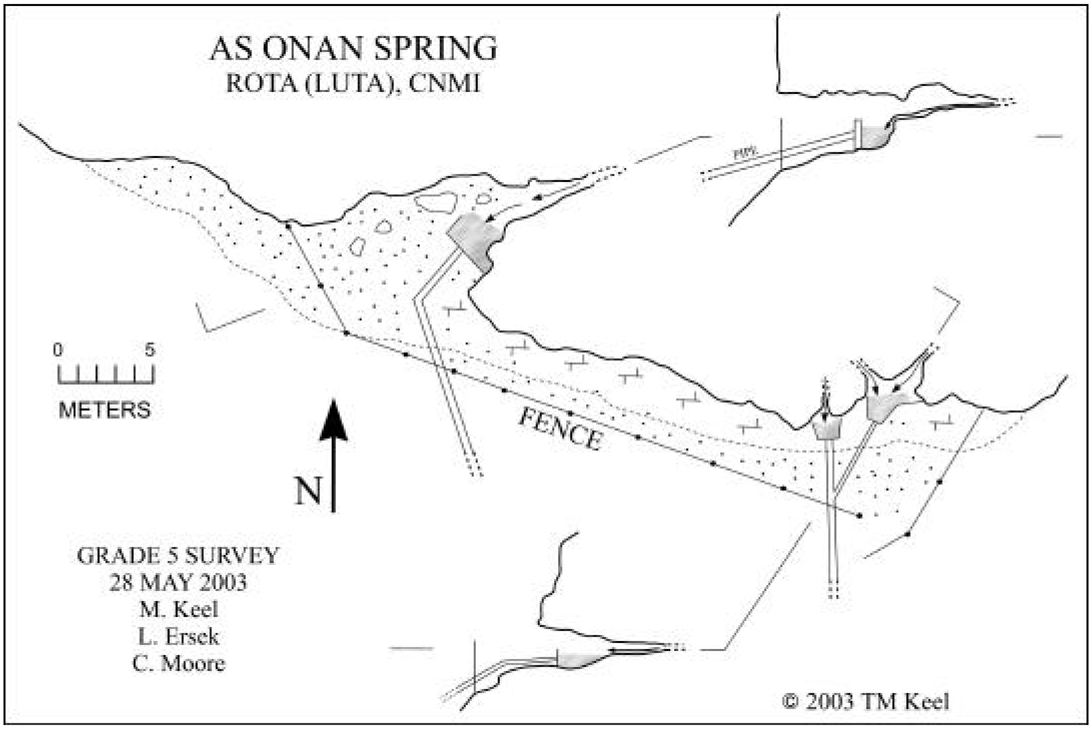

Figure 152: Map of As Onan Spring

Black Cobble Cave

Black Cobble Cave is located at sea level, about 400 m west of the western most stream draining the *Talakhaya*. The cave is about 25 m long, 20 m wide at the entrance and developed along an apparent flow deposit of volcanic material. The volcanic be is prominently visible in the east and west walls of the cave. There is small side room on the east, just inside the entrance. At the back and over part of the front, the floor of the cave is covered with storm washed boulders and cobbles. About 1/3 of the cave floor is covered with an buff-colored (Holocene?) limestone that contains a number of black basalt cobbles that are eroded out in striking contrast to the limestone matrix. Close examination reveals that this buff-colored limestone is stratigraphically above the volcanic deposit, meaning that the buff-colored limestone is younger than the cave.

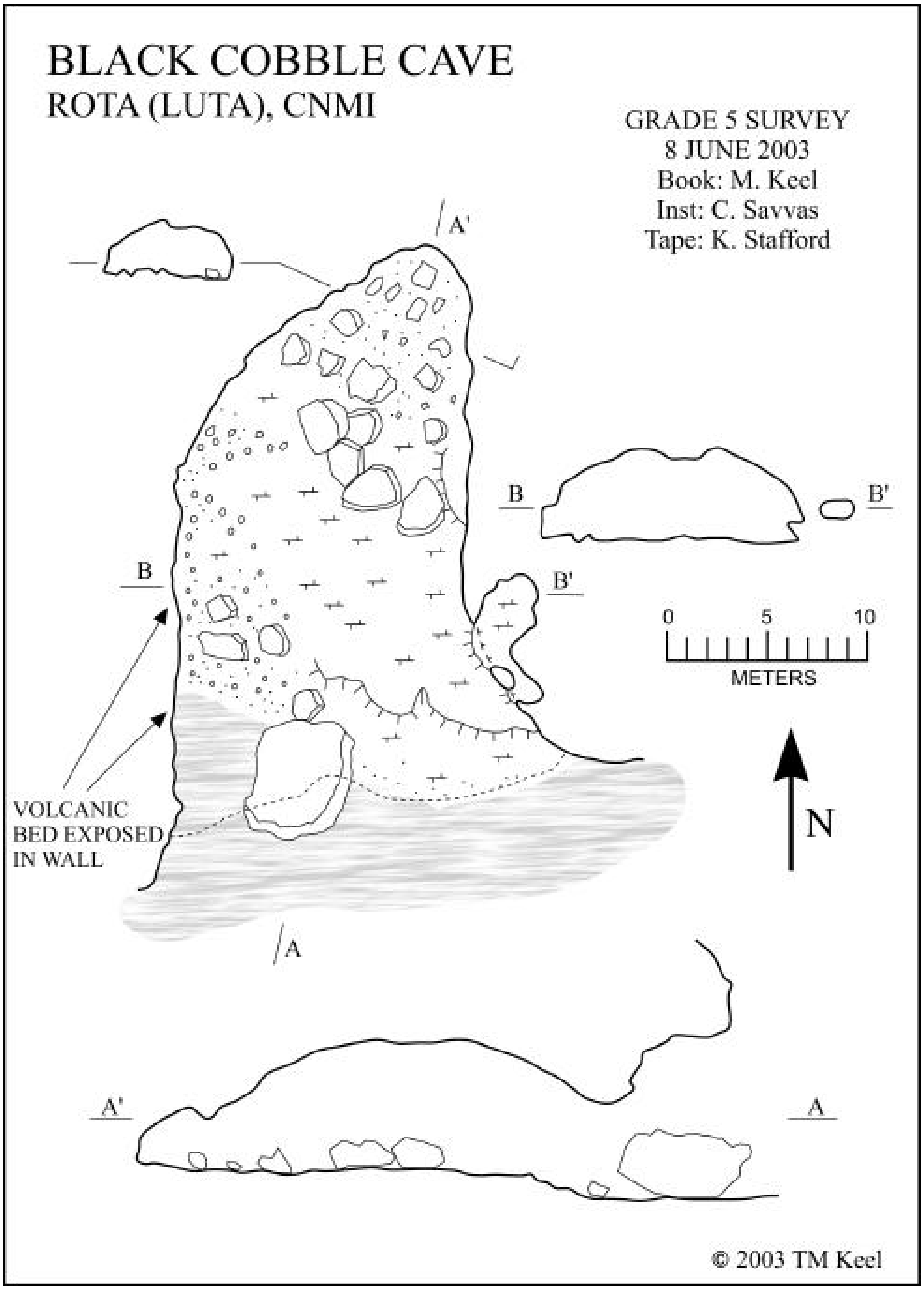

Figure 153: Map of Black Cobble Cave

Discus Cave

Discus Cave was reported by Stafford et al. (2002) as *Sabana* Cave #2. The name is herein changed to Discus Cave. It is located near the limestone/volcanic contact, about 200 m northwest of the Peace Memorial on the *Sabana*. It consists of one shallow ovoid chamber about 3 m across, breached at the top by a 1.5 m hole. This cave does not act as a recharge feature during moderate rainfall, but there are un-enterable recharge features located on the contact within a few tens of meters.

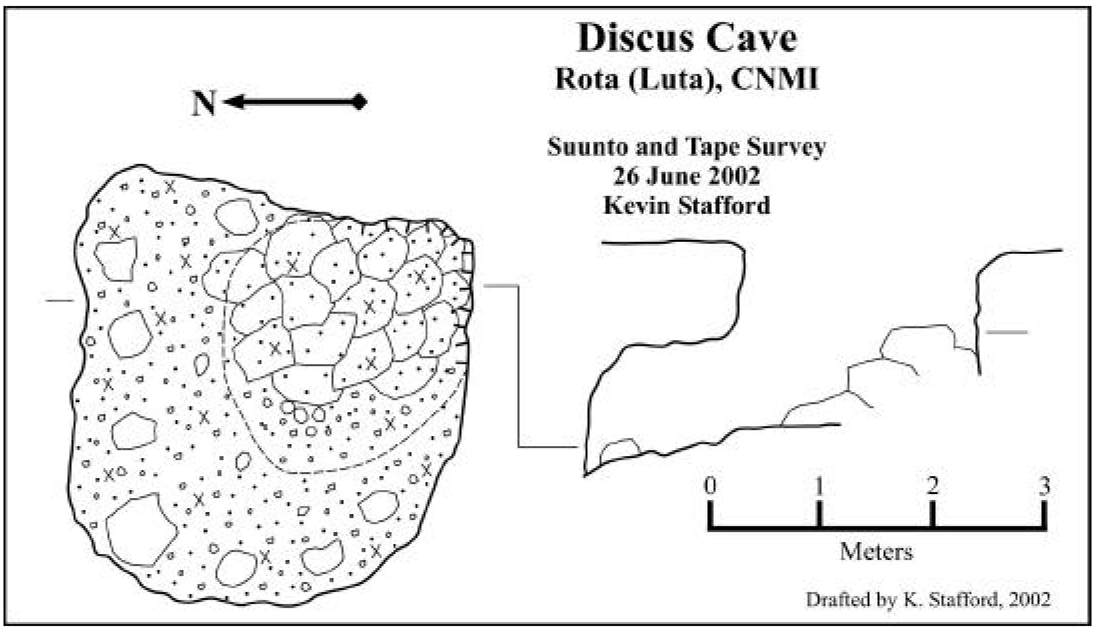

Figure 154: Map of Discus Cave

Gagani Cave

The entrance to *Gagani Cave* is located at the south end of the beach below *Gagani*. The outer part of *Gagani Cave* is only about 10 m long and oriented sub-parallel to the cliff face; north south. Just inside the cave entrance there is a small hole at the floor on the east wall. Beyond this small hole, the cave opens into a room about 6 m wide. The passage leading from the east end of this room continues, ranging from 0.5 to 2.5 high and from 2 to 3 m wide. The floor of this passage rises and falls as much as 2 m. At about 20 m from the entrance, where the main passage turns toward the northeast, a low room opens to the south. About 20 m beyond that, the passage widens to about 5 m. A lead on the northwest side of this room was not explored due to blockage by speleothems. A short climb down in the northeast corner of this room leads to the continuation of the cave. About 10 m beyond the climb down, a room less than 1 m high, 4 to 5 m wide, and about 8 m long opens to the southeast. Just beyond this room, the passage narrows to two very small parallel constrictions the excluded larger explorers. Beyond these constrictions, *Gagani* Cave continues for about 20 m as a room about 1 m high and 4 m wide. The unlike most of *Gagani Cave*, the floor and ceiling of this room are almost completely covered with speleothems. A fracture is visible in the ceiling for almost the full length of *Gagani Cave*. In most places the fracture is tightly closed and very planar, suggesting that the fracture is actually a fault and the planar nature is the result of fault motion. Some of the features in *Gagani Cave* suggest that there might have been fault motion after the cave formed. Several apparent faults are visible on the surface near *Gagani Cave*. Sugawara (1939 [1949]) reports faults in this area.

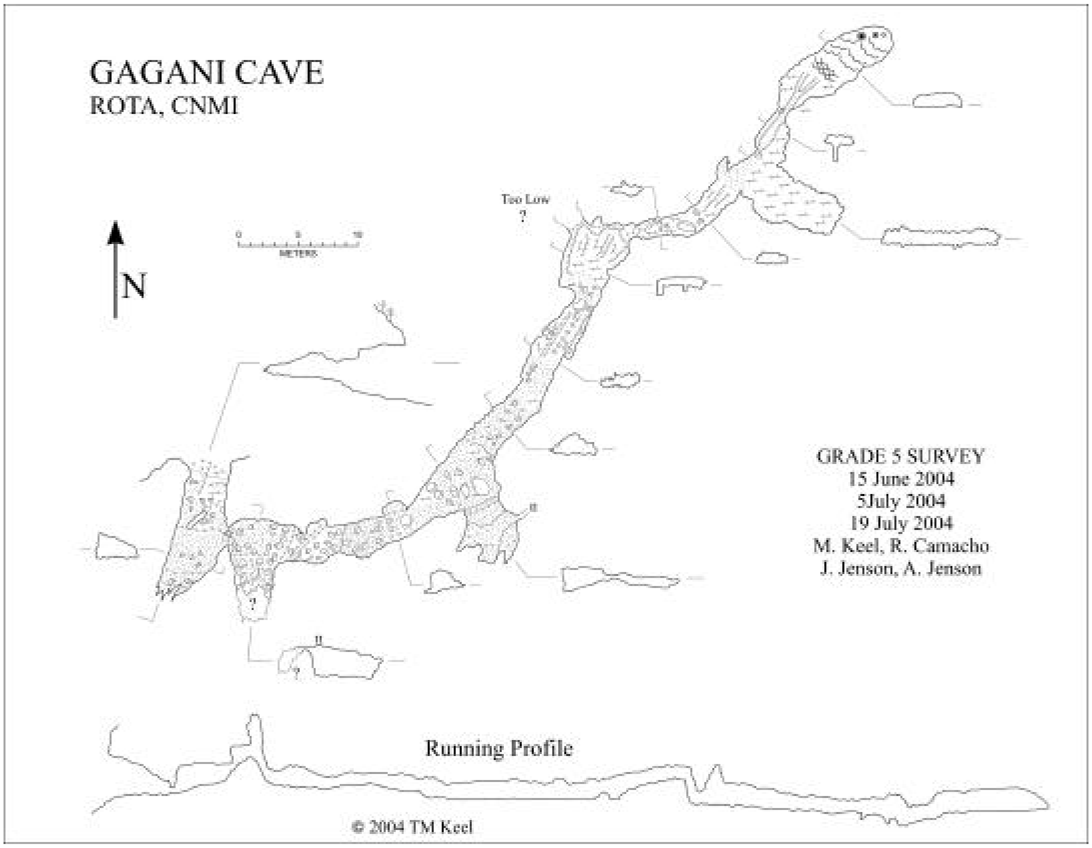

Figure 155: Map of Gagani Cave

North Side Trickle Cave

North Side Trickle Cave is located at the contact of the volcanic rock and overlying limestone, at the base of the cliff at *Uyulan Hulo*, at about 400 m elevation. The entrance to North Side Trickle Cave is about 5 m wide and faces nearly north. The cave quickly narrows such that it is less then 1 m wide at the rear, about 10 m from the entrance. At the rear there is a short climb to a 3 m passage that "doubles back" over the main passage. A small (<1 liter/minute) flow of water was observed coming from the cave on 25 May 2004. The area outside of the cave shows no evidence of ever having significant stream flow.

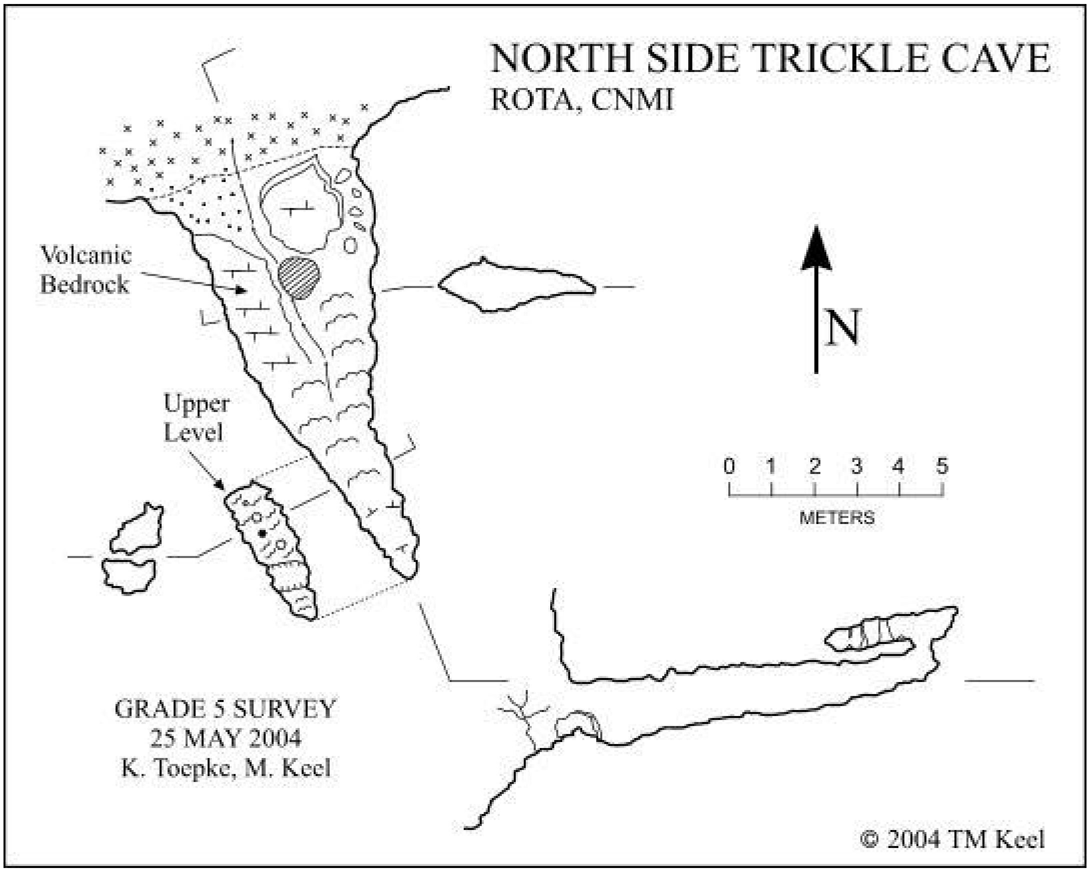

Figure 156: Map of North Side Trickle Cave

Reservoir Cave

Reservoir Cave is located at the contact of the volcanic rock and overlying limestone, at *Uyulan Hulo*, at about 380 m elevation. The 4 m wide entrance to Reservoir Cave faces north and is almost completely blocked with a manmade berm. The inside wall of the berm is stacked stones and the outside slopes down to the natural grade. Behind the berm is a room about 3 m north south and about 7 m east west. The entrance opens at the west end of this room. On 9 July 2004, this room contained a shallow pool of water about 1.5 by 3 meters. At the southeast side of this outer room, the floor rises about 0.5 m at the entrance to a tapering passage. This passage extends about 7 m before narrowing to the point that it is impassable. The trickle of water flowing from this passage into the outer pool was measured at 1 liter per minute. There is no evidence that water ever flows beyond the pool in the entrance room. The ceiling of both parts of Reservoir Cave are very flat and appear to be limestone. The walls appear to be in weathered volcanics.

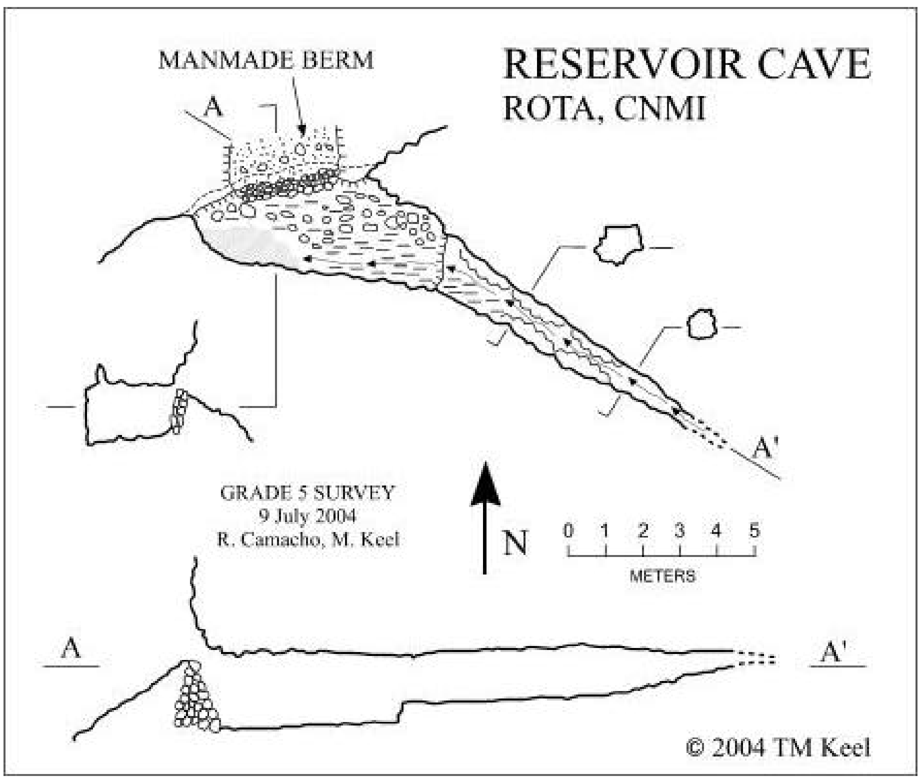

Figure 157: Map of Reservoir Cave

Rota Rooter Cave

This cave was reported by Stafford et al. (2002) as *Sabana Cave* #1. The name is herein changed to Rota Rooter Cave. This cave is located on the *Sabana*, in a banana patch about 150 m northeast of the Peace Memorial. This feature consists of a solutionally modified crack filled with mud at the bottom. It is about 3 m deep, about 3 m long and less than 1 m wide. Observation of this area during a rain event showed that Rota Rooter Cave was not acting as in insurgence. However, there is a major insurgence a few meters away at the low point of the depression.

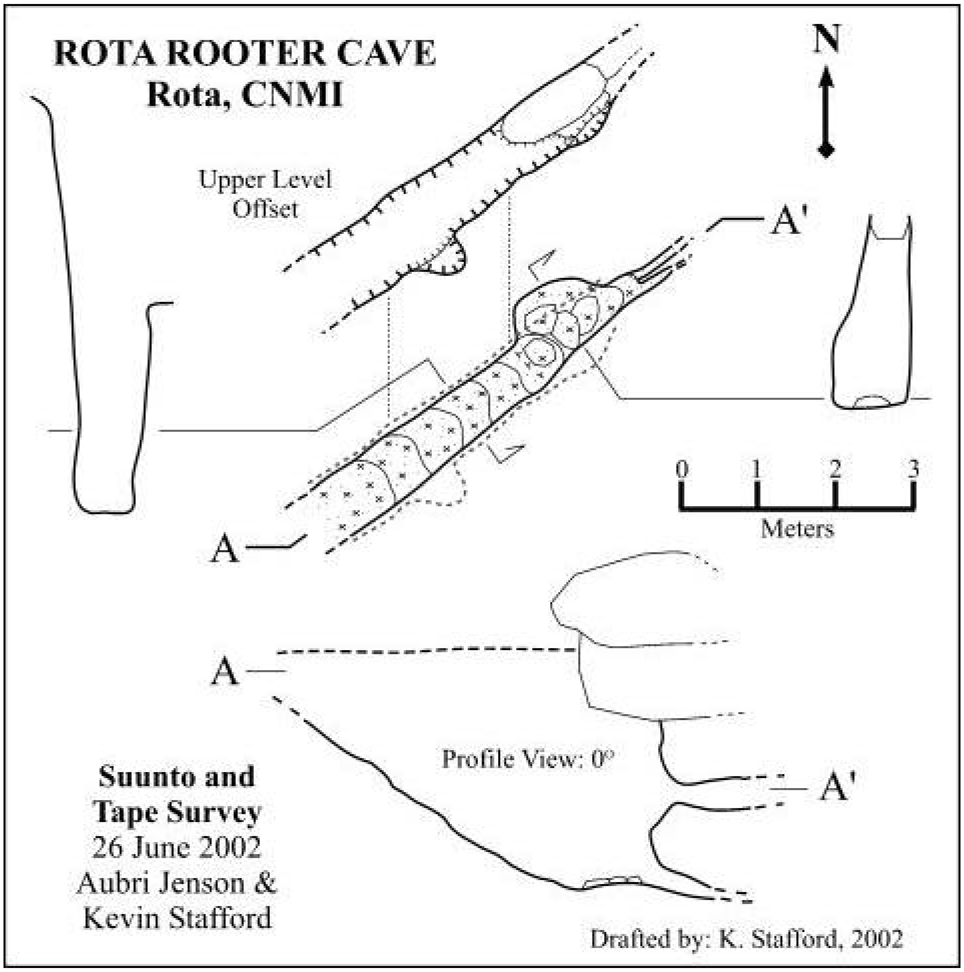

Figure 158: Map of Rota Rooter Cave

Summit Cave

This cave is located at about 470 m elevation, about 300 m south of the summit of Mt.*Sabana* (also known as *Mt. Manila*), the highest point on Rota, at the contact between the volcanic rock exposed on the summit and the limestone. Both entrances are located in a closed depression that is not shown of the USGS topographical map (1999). Up slope from the depression is a groove in the hillside about 15 m wide and about 60 m long that leads to the depression. One entrance to the cave is located at the bottom of the depression at the west end while the other is located about 3 m higher and to the west. The lower entrance leads to a passage 0.5 m high and about 2 m wide. It initially runs south then trends west. After about 12 m it opens into a room with daylight coming in from the higher entrance. This crawlway was surveyed in May 2003 but found to be flooded in January 2004. The main room is about 15 m long and about 11 m wide, trending north south. The floor slopes irregularly from a steep "ramp" leading up to the higher entrance at the north end, down to a depression beside the south wall. It appears that water sometimes flows across the floor of this room and drains through the bottom of the depression. The room does not show any signs of back flooding. Two meters east of the floor depression is a muddy crawlway leading up to a roughly circular room about 4 m in diameter. The flat ceiling of this room is about 5 m high and must be very near the surface.

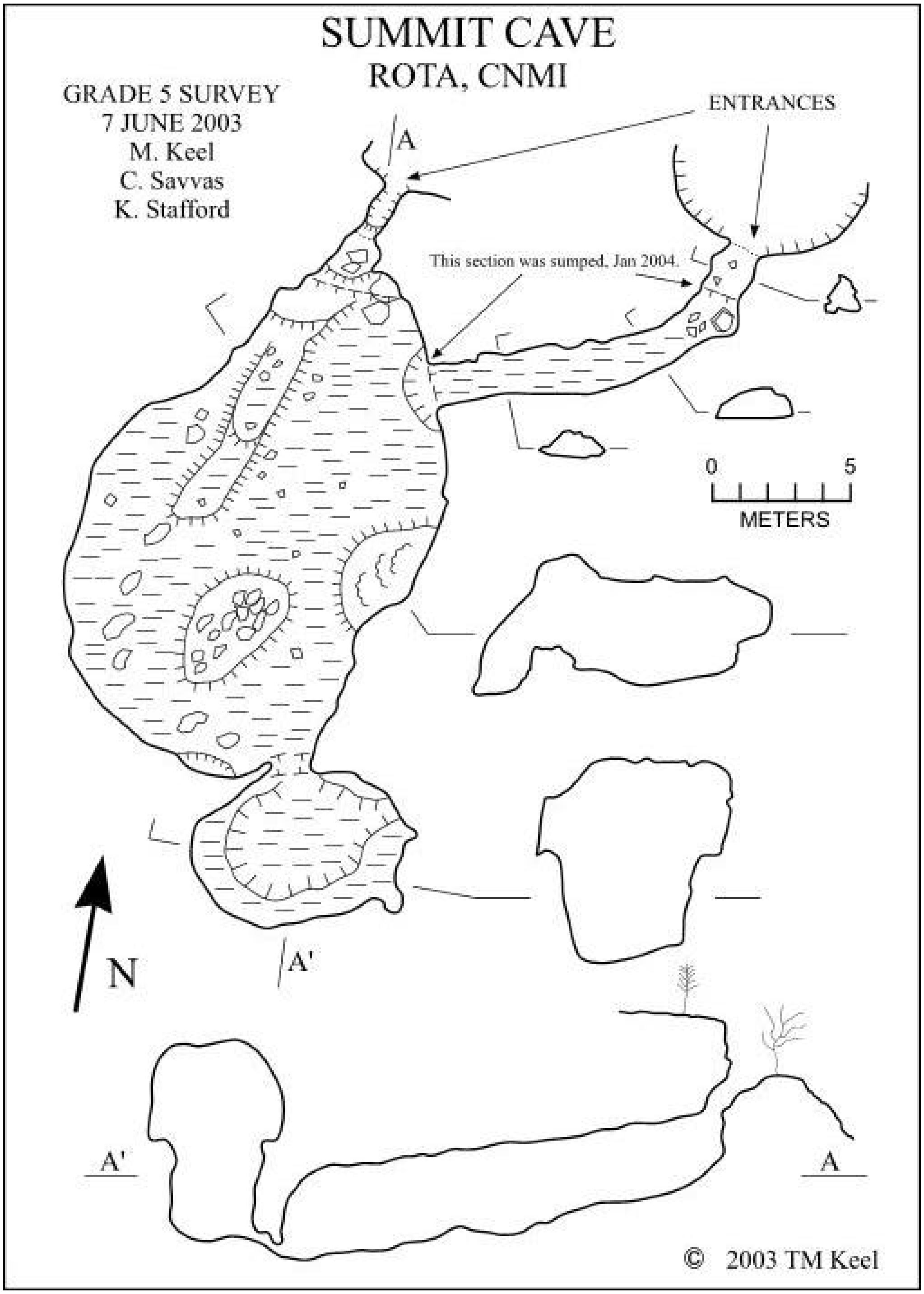

Figure 159: Map of Summit Cave

Fissure Caves

Big Fern Cave

Big Fern Cave is located at about 370 m elevation in *Uyulan Hulo*. Big Fern Cave is a complicated cave developed along fractures that may be related to the very large landslide scar that is located just to the east. Big Fern Cave has two entrances; one of which is the only collapsed sink cave entrance found on Rota to date. The floor of the sink contains vegetation including two large trees and some ferns as tall as 2 m. This sink is clearly the result of the collapse of a cave chamber of considerable size. The sink entrance is about 18 m long and about 7 m wide, oriented east west. The east end of the sink has an overhanging section about 4 m long and about 5 m high. The west end of the sink has a cave-like section that slopes down about 8 m before pinching out. About midway along the north wall of the sink, the floor slopes down and to the north. Under the overhang, one passage runs parallel to the sink and has small openings up to it. Another passage starts as a short climb down. This climb leads to a sloping room about 15 m long that reaches a maximum of about 10 m high. At the west end of this room is a short crawlway between formations into the Pinnacle Room, which receives light from the other entrance. The Pinnacle Room is about 16 m north south and about 13 m east west. The Pinnacle Room dips very steeply to the north, with the floor at the north end about 18 m below the Pinnacle Entrance. The ceiling of the Pinnacle Room is well decorated with stalactites while the floor has stalagmites in some places. Three different passages leading from the lower part of the Pinnacle Room converge and lead down a series of small stair-stepping rooms to a terminal room about 25 m below the surface.

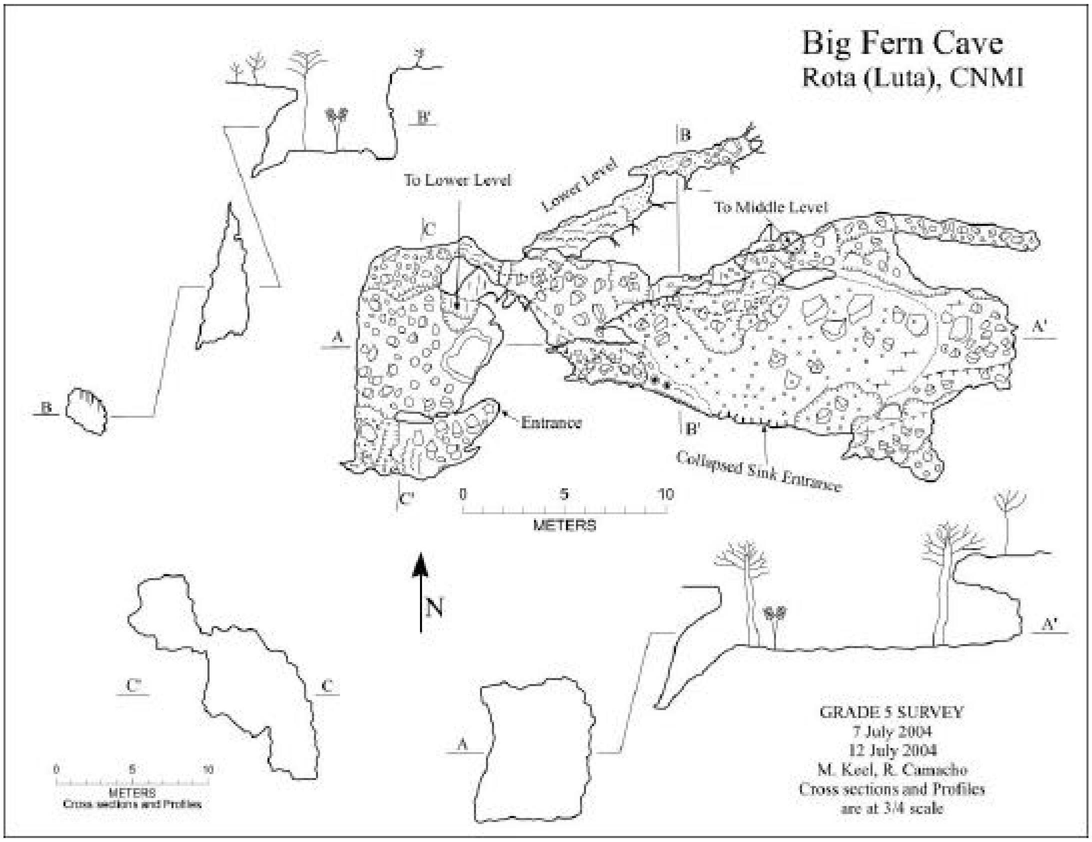

Figure 160: Map of Big Fern Cave

Bitsy Cave

Bitsy Cave is a very small feature just above the active bio-erosion notch, at the west end of the point below *Gaonan*. It is apparently developed as dissolution and physical erosion exploited a crack in the bedrock. Although the vertical part of the cave is far too small to be passable, it does allow light in from the cliff top about 3-4 m above the cave entrance. The drip line of Bitsy Cave merges with the bio-erosion notch on the east side of the cave.

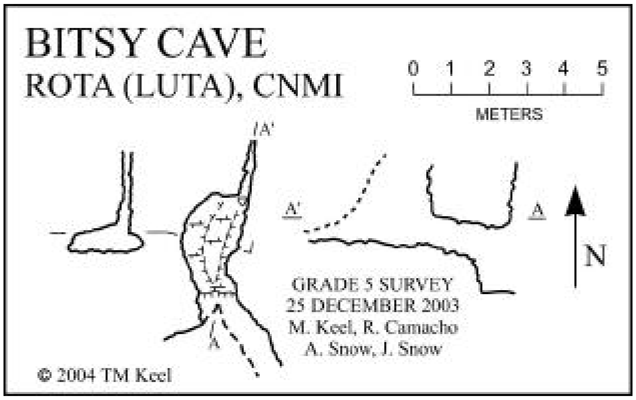

Figure 161: Map of Bitsy Cave

Breeze Cave

Breeze Cave is one of many caves in Fissure City, east of *Uyulan Hulo*, on the north flank of the *Sabana*. The entrance to Breeze Cave is a large overhang open on the south and west. This outer part of Breeze Cave extends about 10 m north south and about 15 m east west. The east end of the outer part of the cave contains several bedrock pillars. The floor of the outer part of Breeze Cave curves steeply down to the north to form a trench. This trench leads to the more enclosed part of the cave that is about 1-3 m wide and extends for about 10 m.

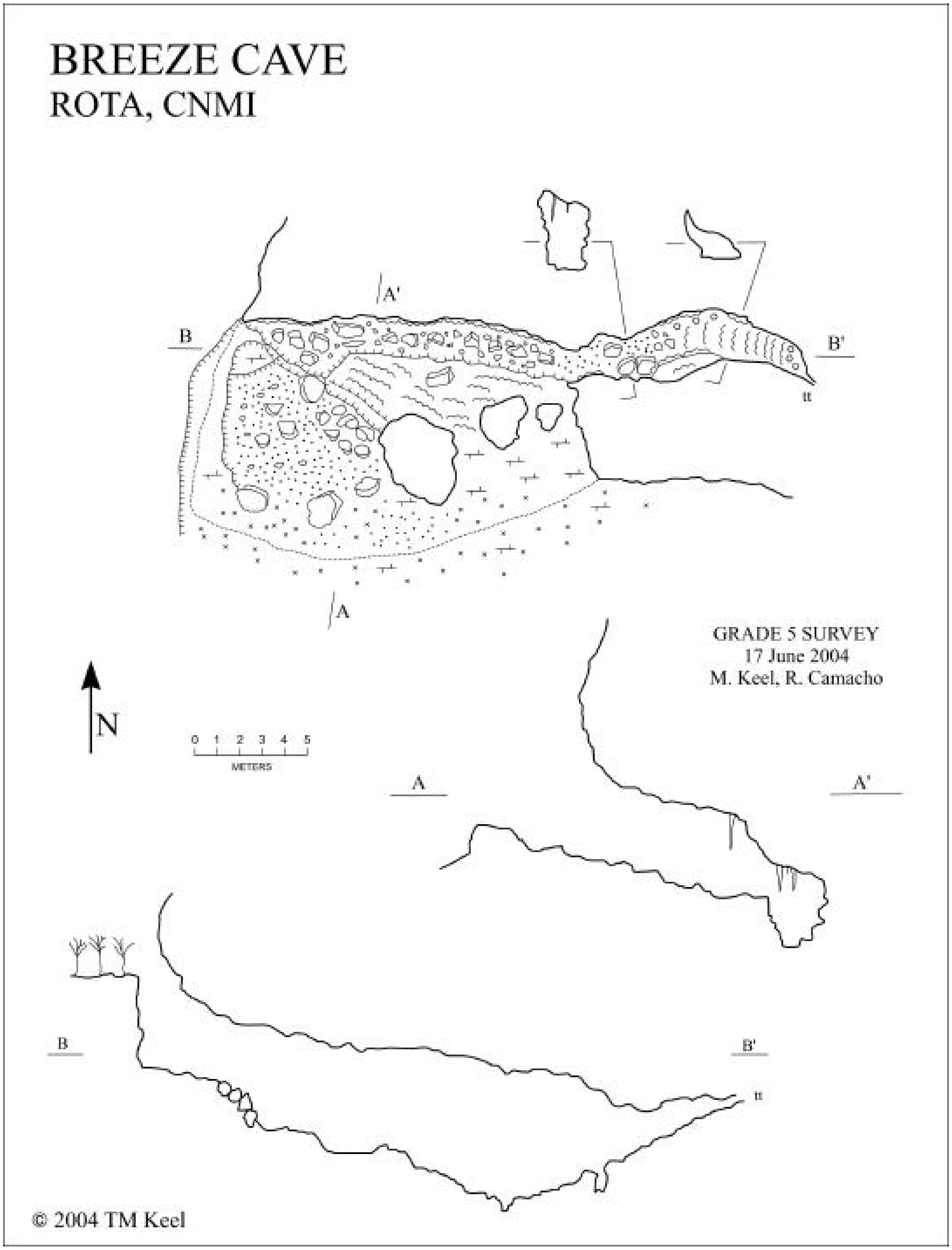

Figure 162: Map of Breeze Cave

Diagonal Fissure

Of the numerous fissures in the *As Mundo* fissure zone, Diagonal Fissure is one of four that were mapped. Diagonal Fissure curves from an east-west orientation at the west end 88 to almost north south at the east end. Diagonal Fissure ranges from about 3 m wide at the west end to less than 1 m at the east end and is about 30 m long. From west to east, the bottom of the fissure falls away such that there is no floor on the east end. The cave continues downward as an impassable fissure. The passable depth of Diagonal Fissure is about 18 m.

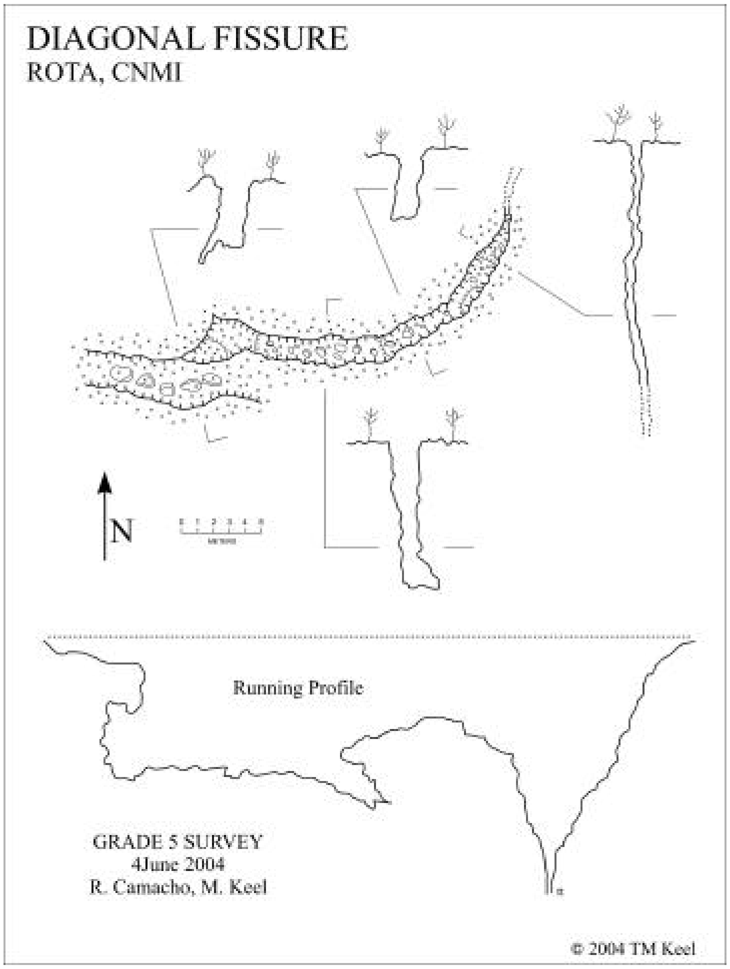

Figure 163: Map of Diagonal Fissure

Fall-In Cave

Fall-In Cave is located near the end of the drivable road at *Uyulan Hulo*. The cave was discovered by literally falling partially into the smaller entrance that is located in the roadbed. Fall-In Cave is a complicated cave developed along fractures that may be related to the very large landslide scar is located just to the east. Climbing down through the Fall-In Entrance leads to the main room of Fall-In Cave. The main room extends for about 22 meters roughly east west. About 4 m from the Fall-In Entrance, the floor drops away and leads down about 8 m to the lower section of the cave. The lower section is parallel to the upper section and is about 15 m long. There is a small room, containing extensive speleothems, extending to the south of this part of the cave. About 8 m east of the Fall-In Entrance the cave branches to the south of the main passage. The south branch extends for about 4 m to the Pineapple Entrance, a climb of about 2 m. Beyond the branch; Fall-In Cave extends for another 14 m. The flow of this section of the cave descends to about 7 m below the Fall-In Entrance.

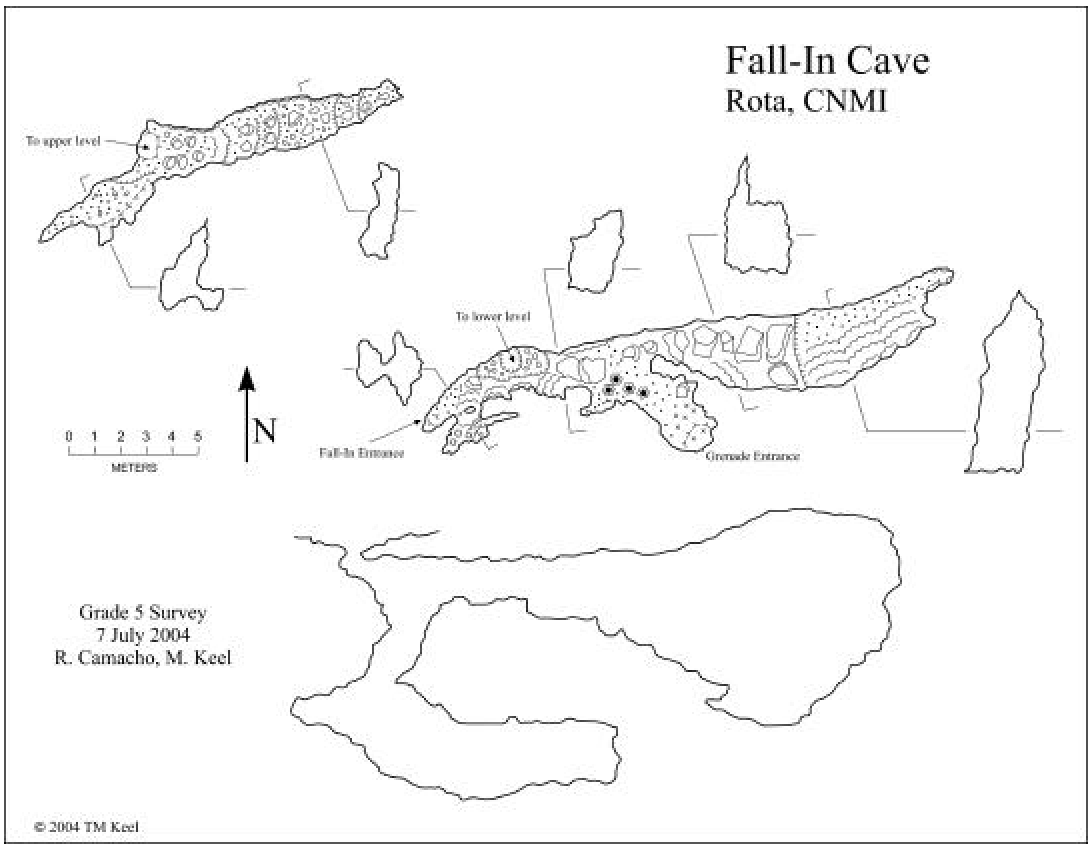

Figure 164: Map of Fall-In Cave

Fissure City Cave

The entrances to Fissure City Cave are located in Fissure City at the bottom of the large closed depression depicted on the USGS topographic map of Rota (1999), east of *Uyulan Hulo*. There are other fissures in the bottom of the same closed depression that has not been mapped. The upper part of Fissure City Cave consists of a connected series of rooms that range from 2 to 5 m wide and from 2 to 10 m high. From the largest room in the upper part of Fissure City Cave a passage leads down along a fracture to a maximum depth of about 35 m below the bottom of the closed depression, making this one of the deepest caves on Rota. The deep passage is a fracture with minimal solutional modification. The passable part of the cave ends but the fracture continues.

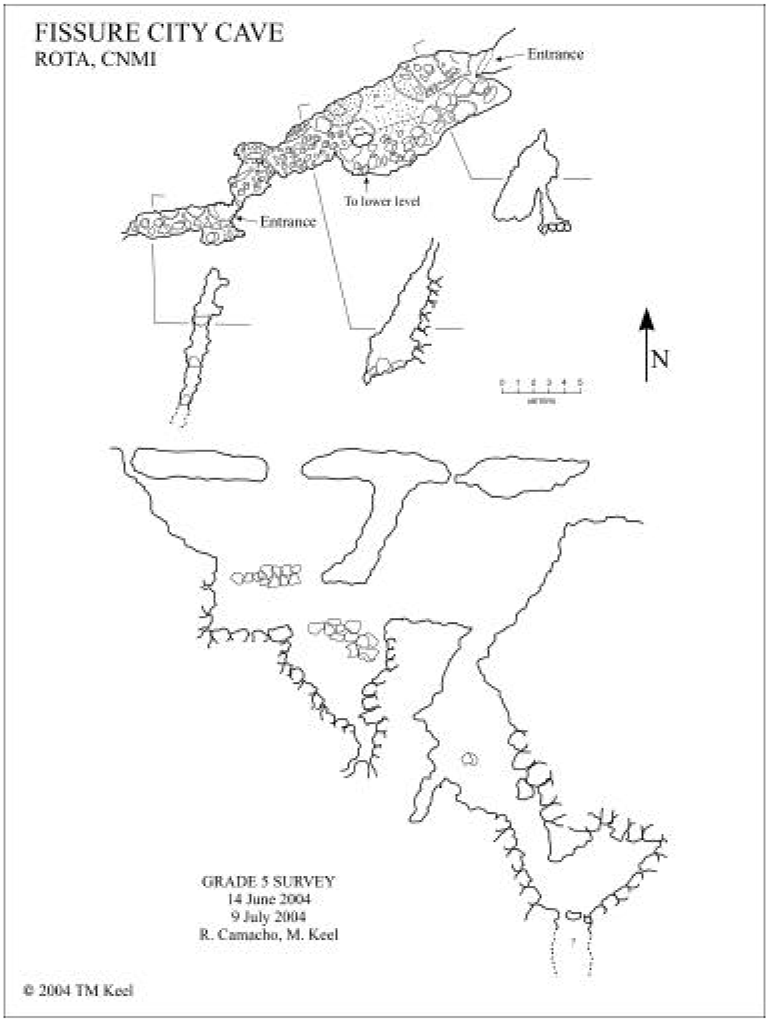

Figure 165: Map of Fissure City Cave

Flange Cave

Flange Cave is located on the northwest side of the *Sabana*, beside the 30 m scarp that strikes at 55 degrees east of north. Flange Cave is a relatively small but complicated that is apparently a fragment of a previously larger cave developed along a possible fault. The southern branch of the cave has man-made steps leading down to a room about 4 m long and about 3 m wide and two small passages which dead end. The northern branch leads to a second entrance on the left about 9 m in, then continues for about 15 m more, to an impassable hole that connects to another small segment of cave that is accessible from the outside.

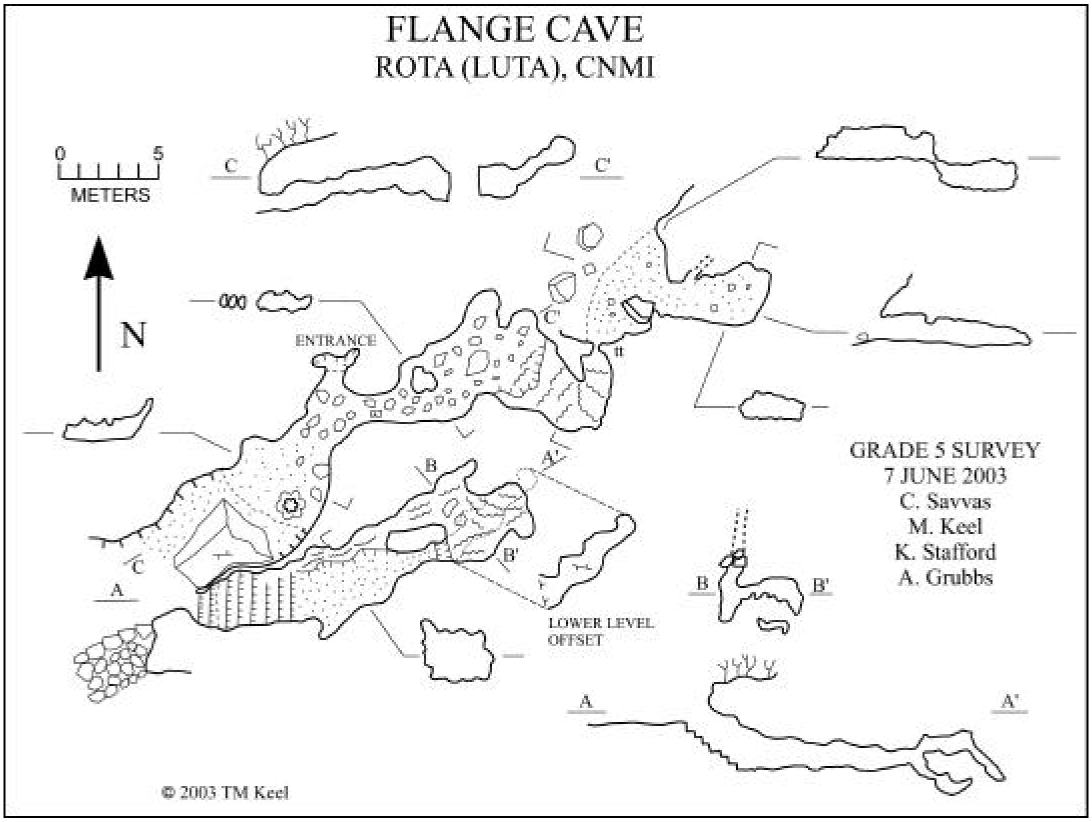

Figure 166: Map of Flange Cave

Green Fissure Cave

Green Fissure Cave is located adjacent to Breeze Cave in Fissure City, east of *Uyulan Hulo*. Green Fissure Cave is oriented northeast southwest. The northeast end is an open sink about 3-4 m wide and up to 3 m deep that leads down into the cave. The cave appears to be developed along two near parallel fractures. The fracture on the north leads up to a skylight entrance. Excluding the sink, Green Fissure Cave is 4-5 m wide, 10 m long and about 7 m tall.

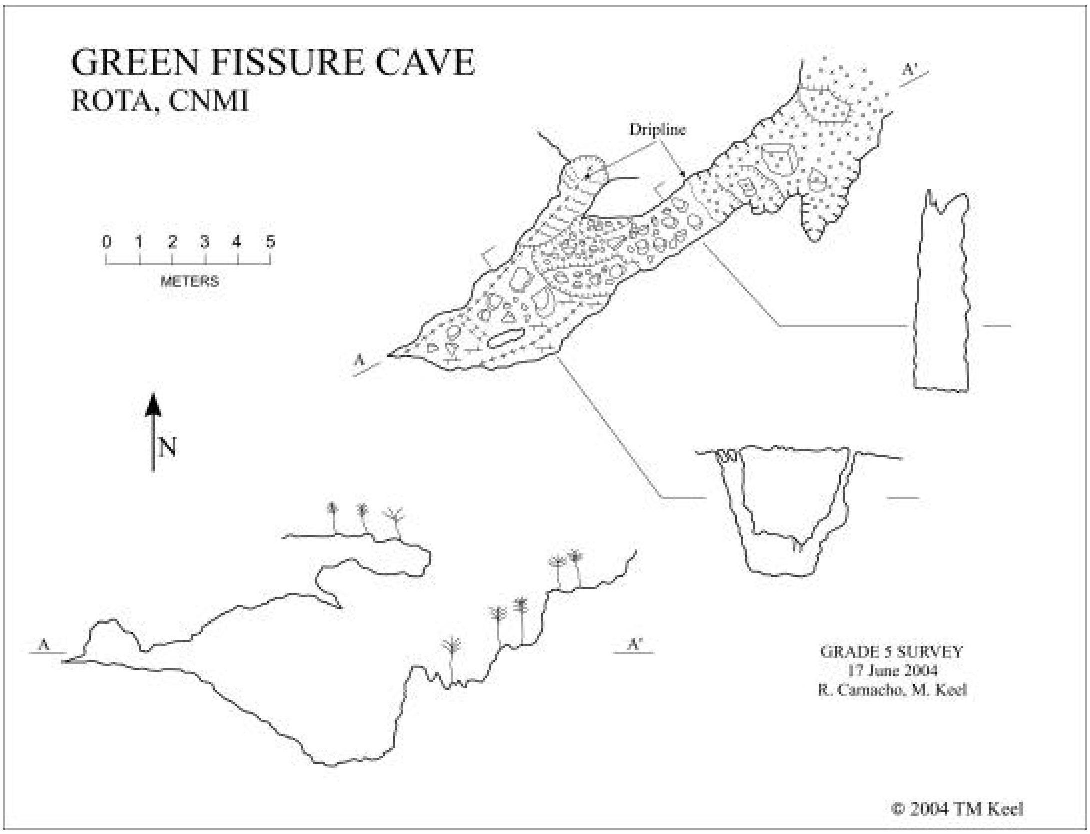

Figure 167: Map of Green Fissure Cave

Henry Fissure Cave

Henry Fissure Cave is located in the northern part of the *As Mundo* fissure zone. Henry Fissure is oriented roughly WNW-ESE but is not linear. It can probably be best described as a series of linear segments of lengths from 3 to 10 m. The depth of Henry Fissure varies from 3 to 14 m. About midway along the length of Henry Fissure, a shallower fissure extends to the south. This shallow side fissure continues straight for about 10 m before it the depth tapers to zero. About 15 m of the west end of Henry Fissure is roofed cave. The passage is mostly less than 1 m wide, with the ceiling 10-12 m high. The traversable part of the cave ends where the fracture becomes to narrow.

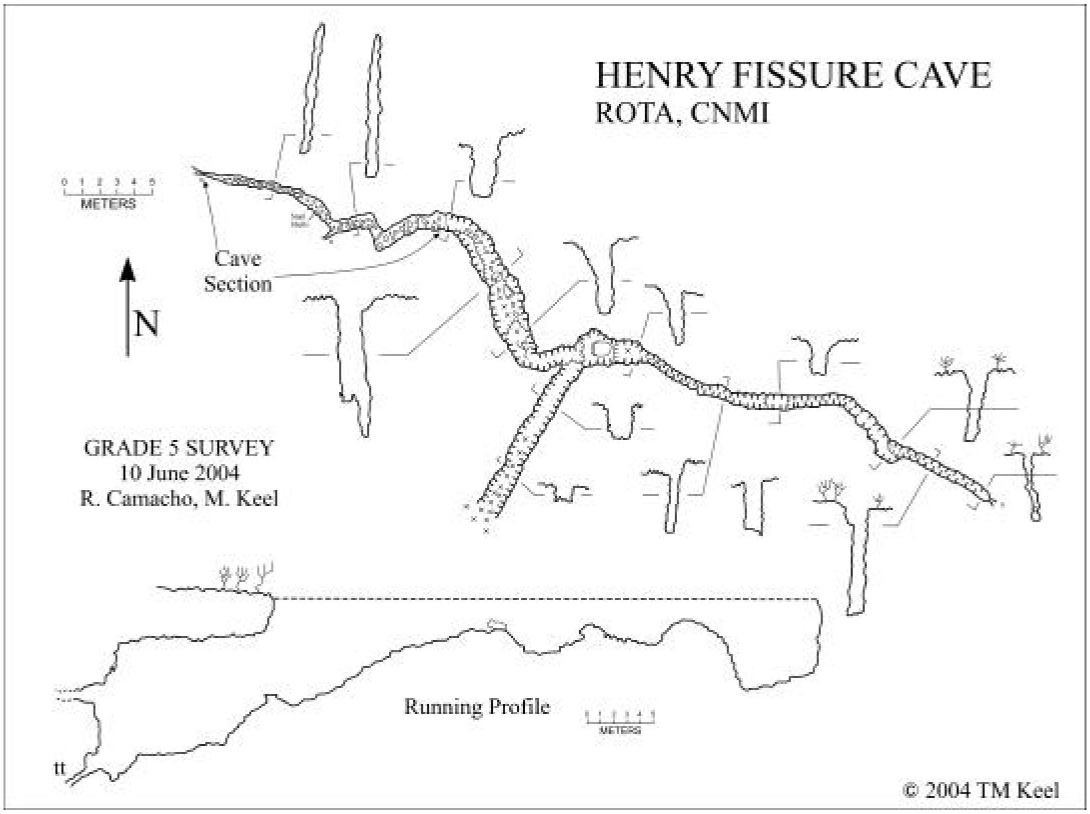

Figure 168: Map of Henry Fissure Cave

Jug Handle Cave

Keel (2005) did not provide any information on Jug Handle Cave in his thesis; however, T. M. Keel did provide me with a map and location data. From that information, it was determined that Jug Handle Cave is a fissure cave in the *Sabana* Region.

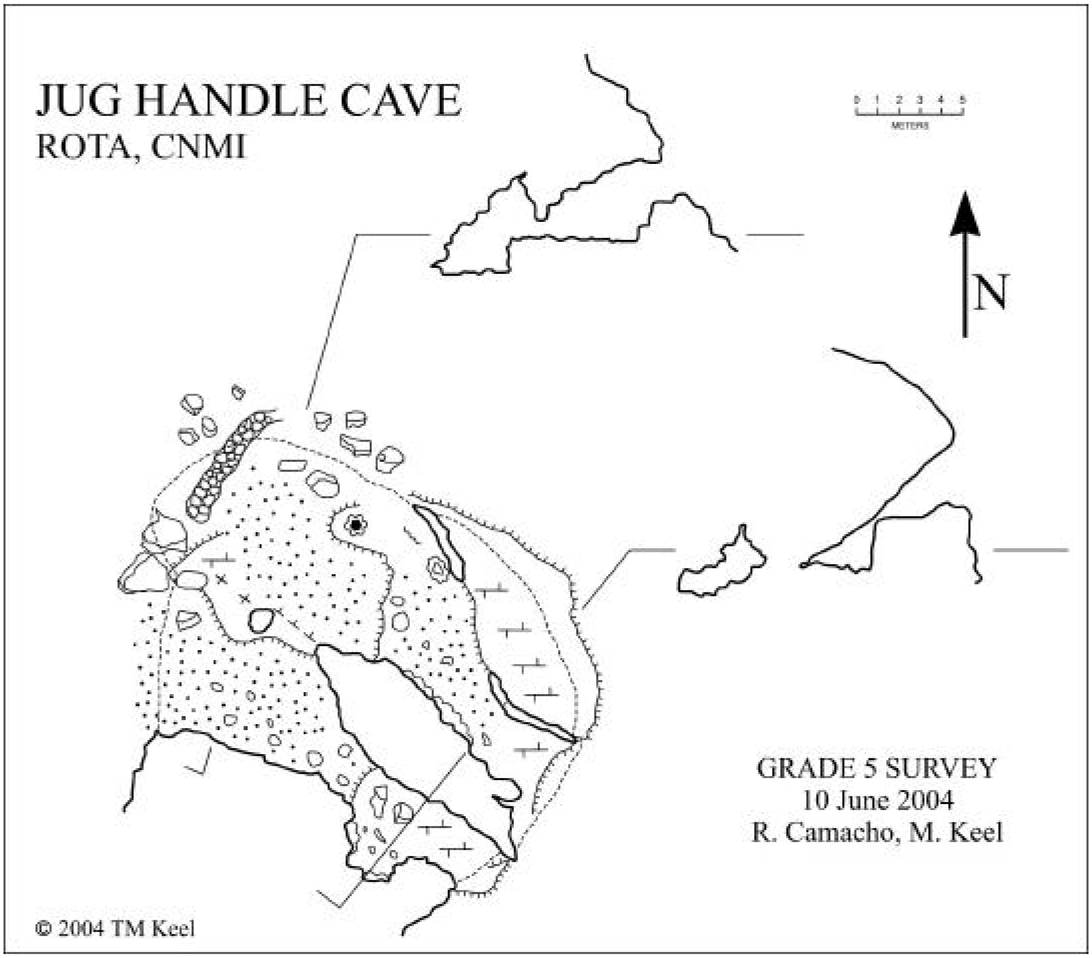

Figure 169: Map of Jug Handle Cave

Mosquito Fissure

Mosquito Fissure is a 13 m long fissure segment located in the southeastern part of the *As Mundo* fissure zone. It averages about 1 m wide and ranges from 4 to 7 m deep and is oriented about 55 degrees west of north.

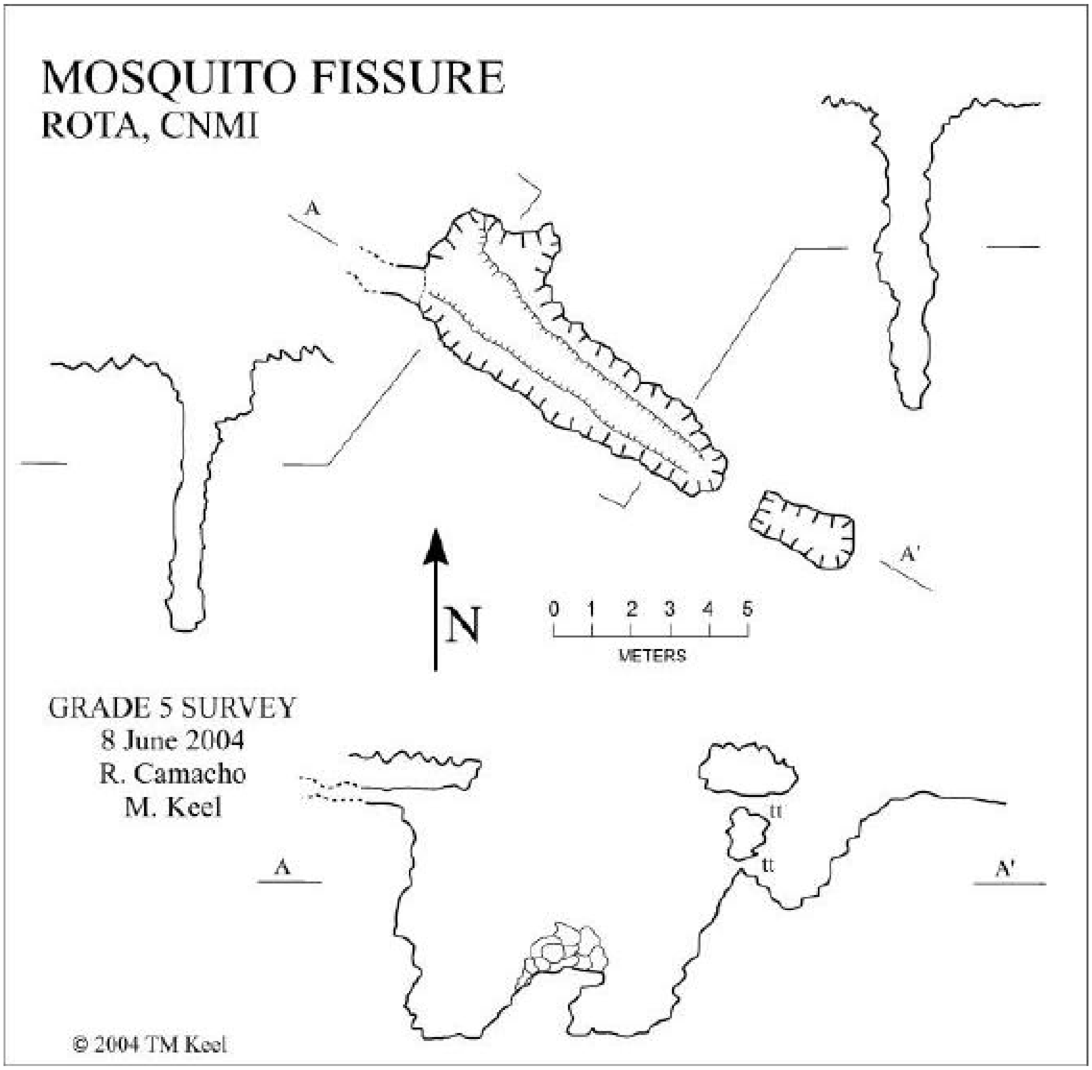

Figure 170: Map of Mosquito Fissure

One Shot Cave

One Shot Cave is located near *Liyang Alapin*, north of the *Poña Point* overlook. The cave is about 5 m long, 1-1.5 m wide and about 1-2 m high. The floor of One Shot Cave is primarily bedrock with some soil and a few secondary formations.

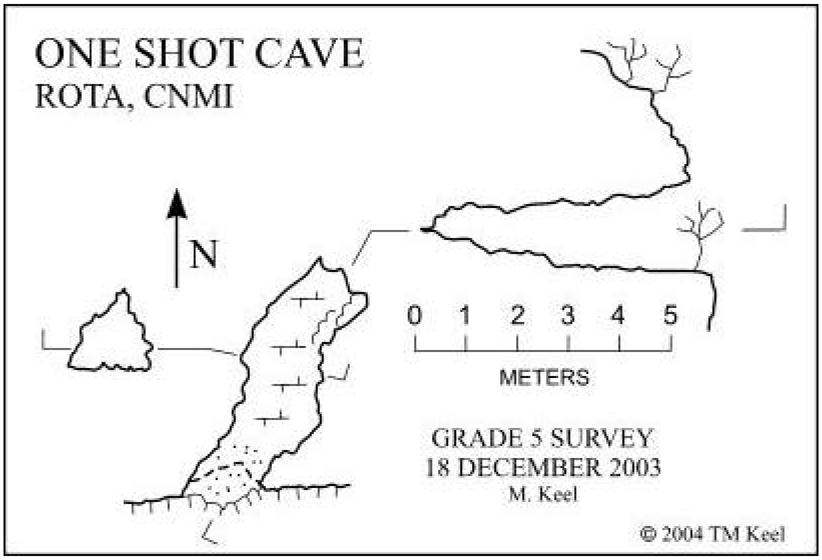

Figure 171: Map of One Shot Cave

Root Wall Cave

Root Wall Cave is located in Fissure City, east of *Uyulan Hulo*. The entrance to Root Wall Cave is in an area of rugged pinnacle karst that also contains the entrances to some smaller caves that were not mapped. The entrance to the cave is divided by a moss covered "curtain" of roots, growing from the ledge above, thus the name Root Wall Cave. The central room in Root Wall Cave spans about 8 m by 8 m and has a floor sloping to the south. The south wall of the central room has speleothems that are several degrees from their original growth position, indicating relatively recent movement of the fractures along which Root Wall Cave is developed. From the south side to the central room, a passage extends down into a smaller room floored in breakdown. There is a small passage extending down into the breakdown for a short distance. There are upper and lower passages extending from the northeast corner of the central room. The lower passage is reached by a 2 m climb down and is developed along a linear fracture oriented 60° east of north. This passage continues for about 12 m to a 3+ m climb down. Root Wall cave has not been explored beyond this climb down. The upper level leading from the central room is about 5 m long, oriented 60° east of north, has a floor sloping steeply to the southwest and is densely decorated with speleothems. Root Wall Cave is developed along a complex set of fractures that show evidence of substantial motion since the cave developed.

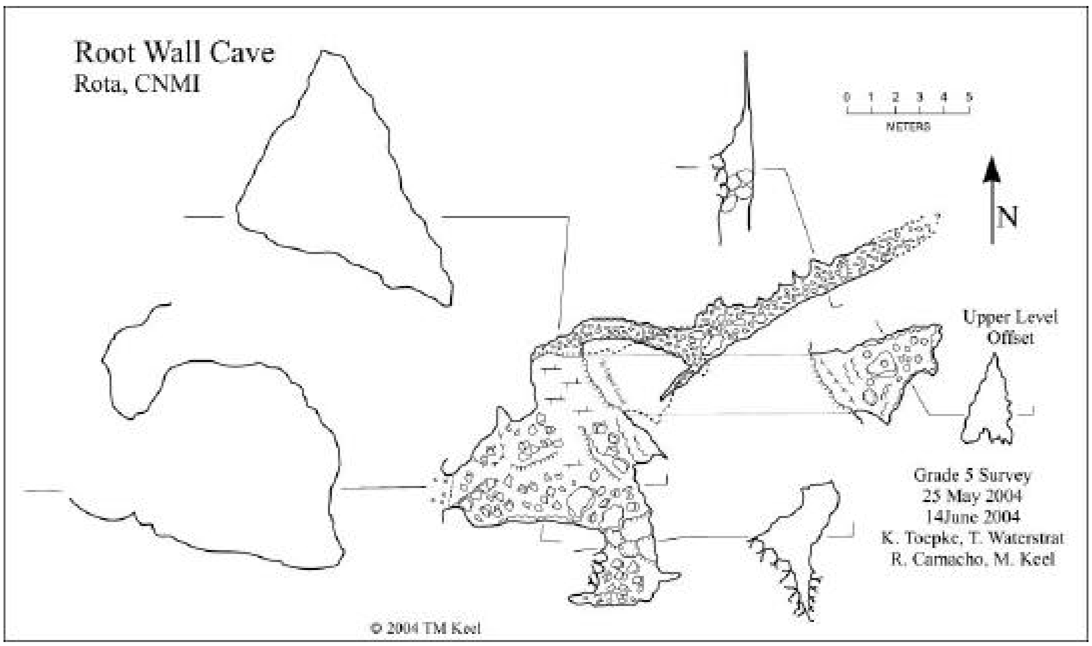

Figure 172: Map of Root Wall Cave

Tea Kettle Fissure

Tea Kettle Fissure is located in the *As Mundo* Fissure Zone adjacent to the south side of the road through this area. Tea Kettle Fissure consists of three segments. The westernmost segment is about 47 m long, 5-8 m deep and about 10 m wide. The middle segment is a more open area about 30 m wide extending about 25 m to the southeast. A shallow extension of the middle segment runs parallel to the westernmost segment. East of the open middle segment and aligned with it, is a much narrower 20 m long segment that includes roofed cave sections at each end. This easternmost segment is about 10 m deep and floored with boulders jammed in the fissure. Small passages can be seen extending below the floor.

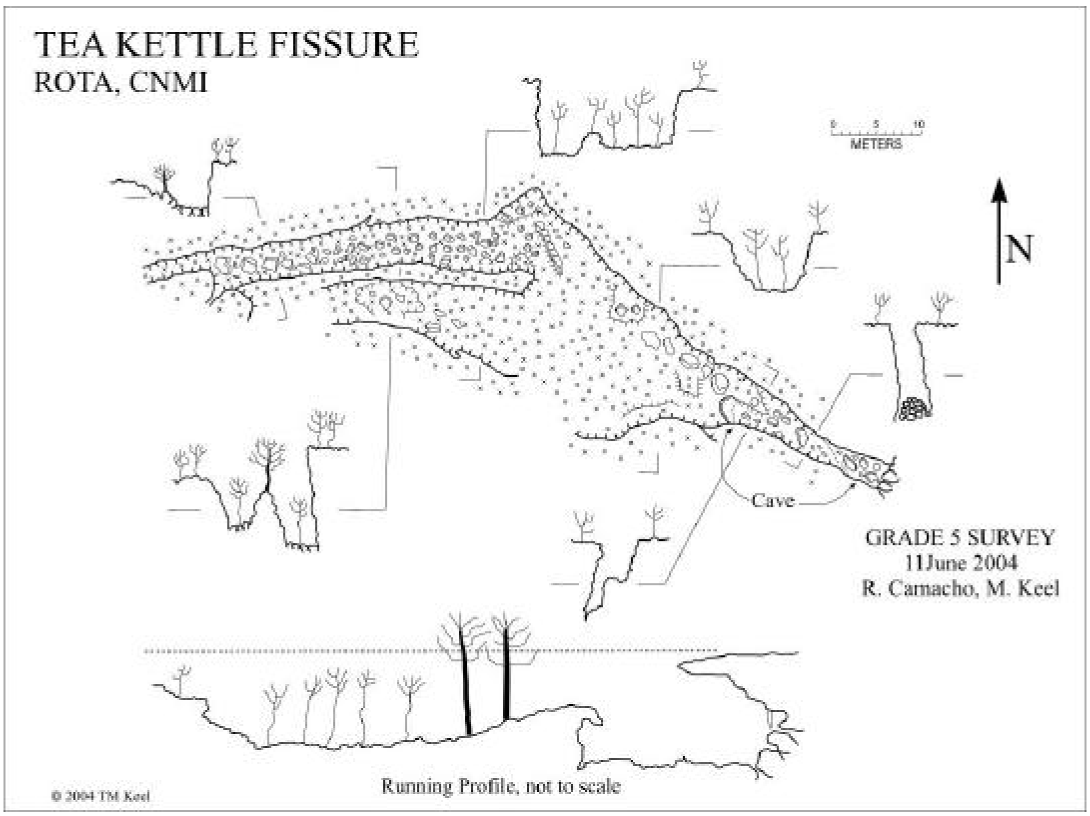

Figure 173: Map of Tea Kettle Fissure

Village View Cave

Village View Cave is located in the cliff face near the southeast end of *Tachok*, near *Songsong* Village and is visible from the road. Village View is a complicated cave consisting of two open, solutional chambers the larger of which is intersected by a large fracture that is apparently younger than the cave. The smaller northern chamber is about 12 m long, 3 m wide and 2.5 - 3 m tall. It widens to 5-6 m near the back before ending in two pinch outs. This part of the cave is floored mostly with loose sand a few breakdown boulders near the entrance. This northern chamber is connected to the larger part of the cave though a body-sized hole. The larger part of the cave is about 10 m tall at the drip line and very open except for a smaller chamber at the back. The floor climbs steeply at first, then more gradually over breakdown such that the ceiling height is less than about 7 m. On the south side of this larger chamber, a passable bedrock fracture intersects the cave. About 5 m into this fracture it turn roughly 90 degrees to the south and extends out to the cliff face. This crack extends up to the surface above the cave and out to the cliff face. The relative lack of dissolution and deposition in this crack suggests that it is significantly younger than the solutional part of the cave.

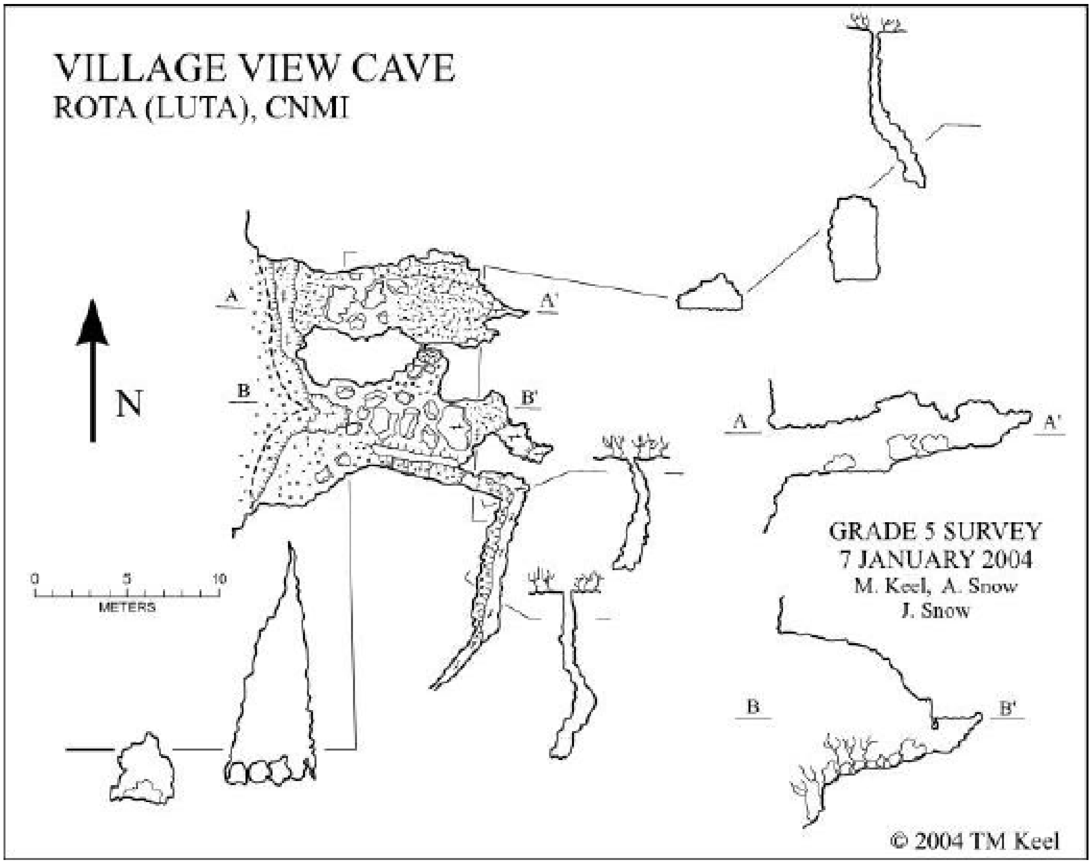

Figure 174: Map of Village View Cave

Flank Margin Caves

Agrippa Cave

Agrippa Cave is one of several caves along the coast between *Poña Point* and *Okgok*. *Agrippa* is distinctive from the other caves in this area in that it is about 2 m directly above a spring that is discharging about 1m above sea level. The spring apparently discharges above sea level due to being perched on volcanic bedrock. Despite *Agrippa* Cave's proximity to an active spring, the shape of this cave suggests flank margin development. The cave is about 8 m long and 5 m wide. At the entrance it widens to about 8 m. The cave is about 1 m high throughout except for being somewhat taller at the entrance. Near *Agrippa* Cave, above the active spring, is a very small hole that appears to be a paleo-spring conduit.

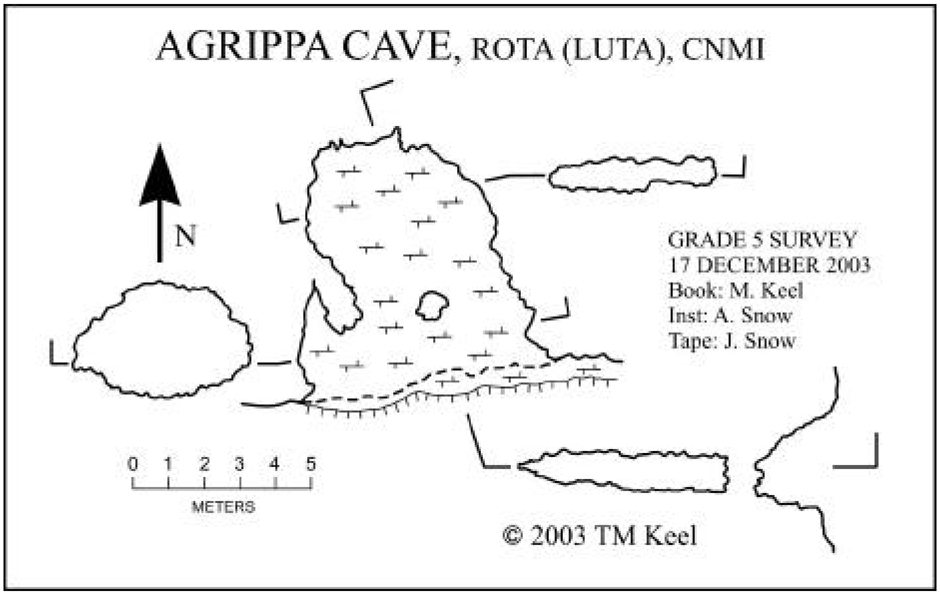

Figure 175: Map of Agrippa Cave

Alaguan Bay Cave

Alaguan Bay Cave is located on the south side of the embayment at *Alaguan* Bay at about 50 m elevation. The entrance is 4 m wide and 2 m high and extends for 3 m before the cave opens up into an irregular chamber 20 m long and 12 m wide. Off this room are a few small chambers, all higher than the main floor. The walls and floor at the rear of the main chamber are covered with flowstone and stalagmites. The ceiling and walls of this cave show strong evidence of the bouldery facies that that the cave is apparently developed in. One boulder visible at the back of the cave is about 3 m in diameter. Based on the location and the shape, this is apparently a flank margin cave.

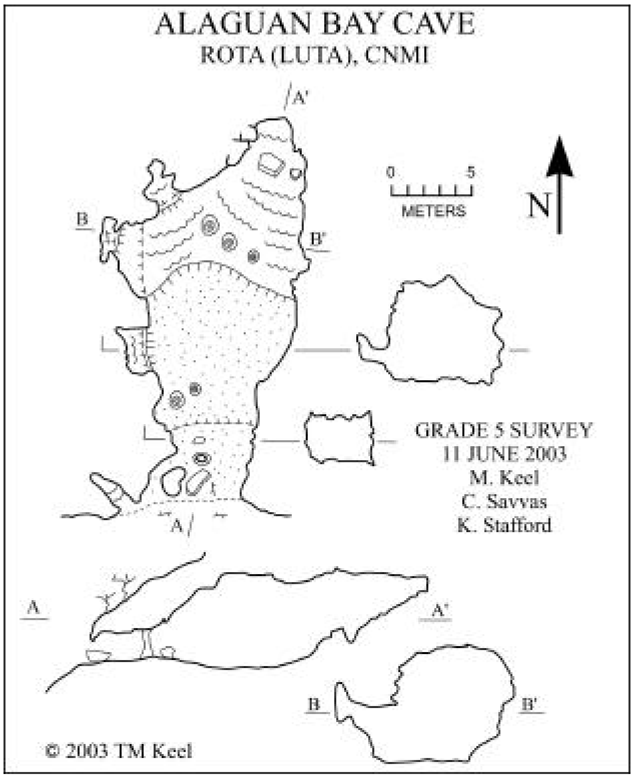

Figure 176: Map of Alaguan Bay Cave

Alaguan Cave

There was no description provided for this flank margin cave.

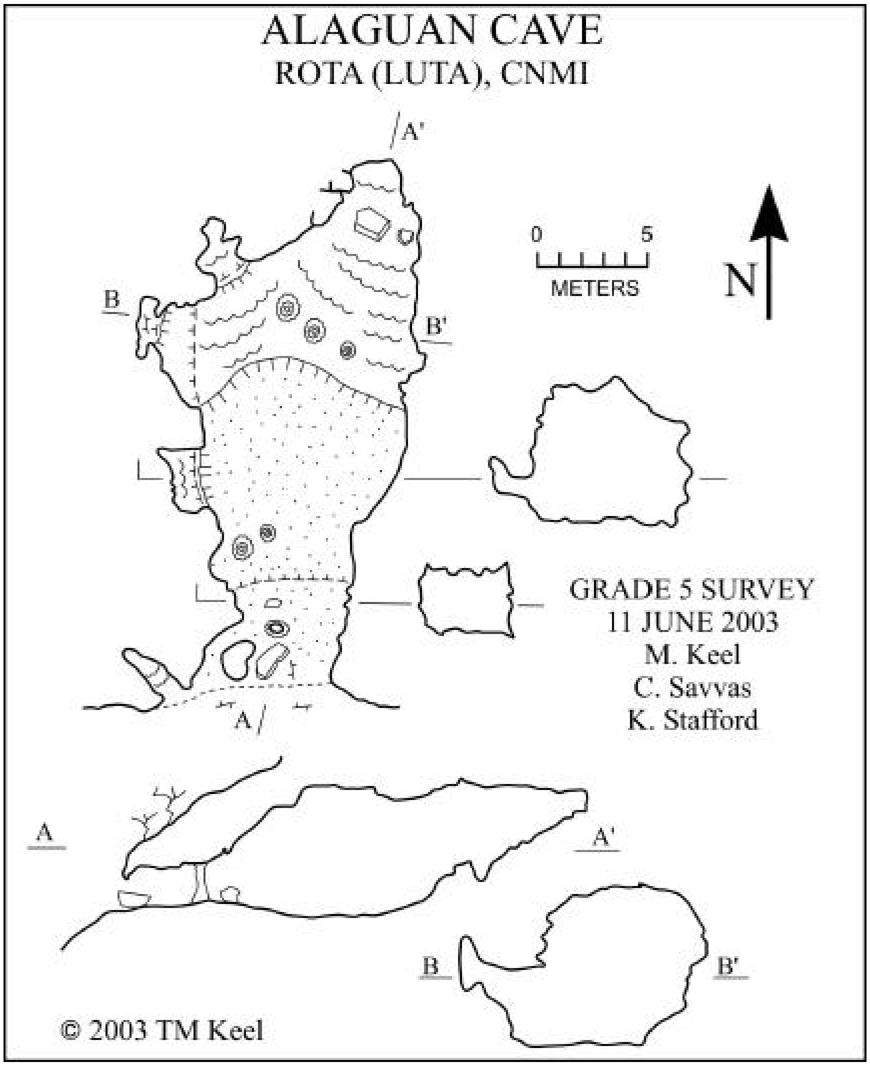

Figure 177: Map of Alaguan Cave

Alaguan Feature A2

Alaguan Feature A2 is located south of the large embayment at *Alaguan* Bay and is documented as an example of the features that are visible from sea and appear to be large cave entrances but which contain no significant cave. It is a shallow rock shelter developed along a fracture in the cliff face. There is one small indentation high in the cliff face, the back of which is not visible from ground level. This feature may represent a mixing zone Mixing-zone Fracture Cave that never developed because fresh water that it might have discharged, was diverted to another fracture, perhaps nearby Deer Cave.

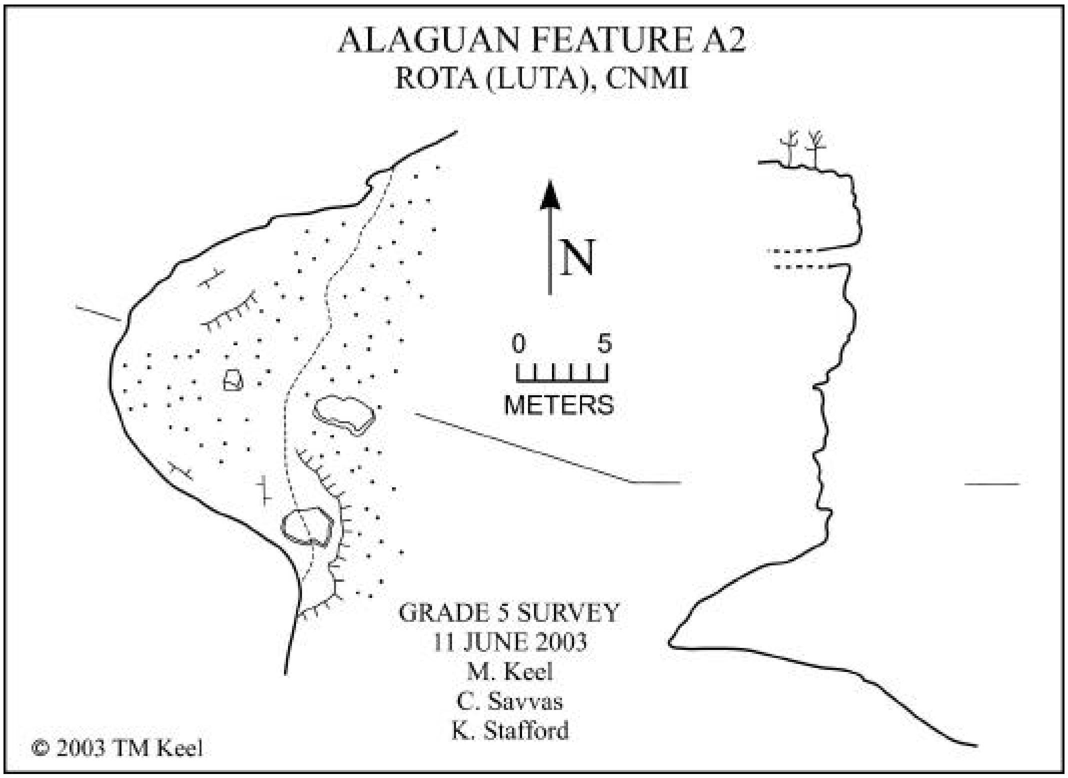

Figure 178: Map of Alaguan Feature A2

Alaguan Feature A3

Alaguan Feature A3 is located south of the large embayment at *Alaguan* Bay and is documented as an example of the features that are visible from off shore and appear to be large cave entrances but which contain no significant cave. This feature is apparently developed along a fracture in the bedrock and extends back from the face of the cliff for about 10 m. The feature is about 3 m wide and the main part is about 10 m high. There is a fissure in the ceiling that extends upward an undetermined distance. The floor is covered with boulders so that its shape of the bedrock below cannot be determined.

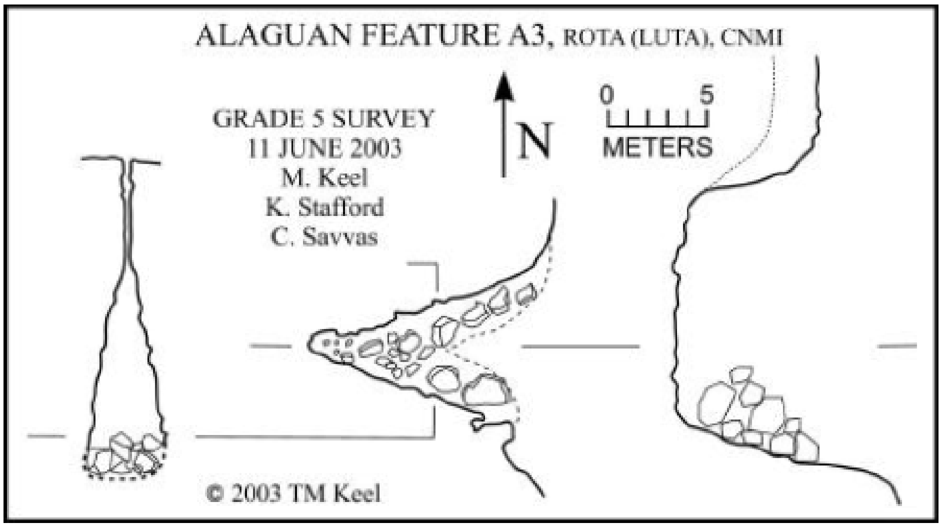

Figure 179: Map of Alaguan Feature A3

Alapin Two Cave

Alapin Two Cave is a few meters from the entrance to *Liyang Alapin*, in the cliff face inland from *Poña Point*. It is apparently a remnant of a formerly larger flank margin cave. The cave is about 8 m wide, about 2 m high across most of its span and is divided by a bedrock wall near the rear. In plan view, the cave is a truncated oval about 6 m in diameter.

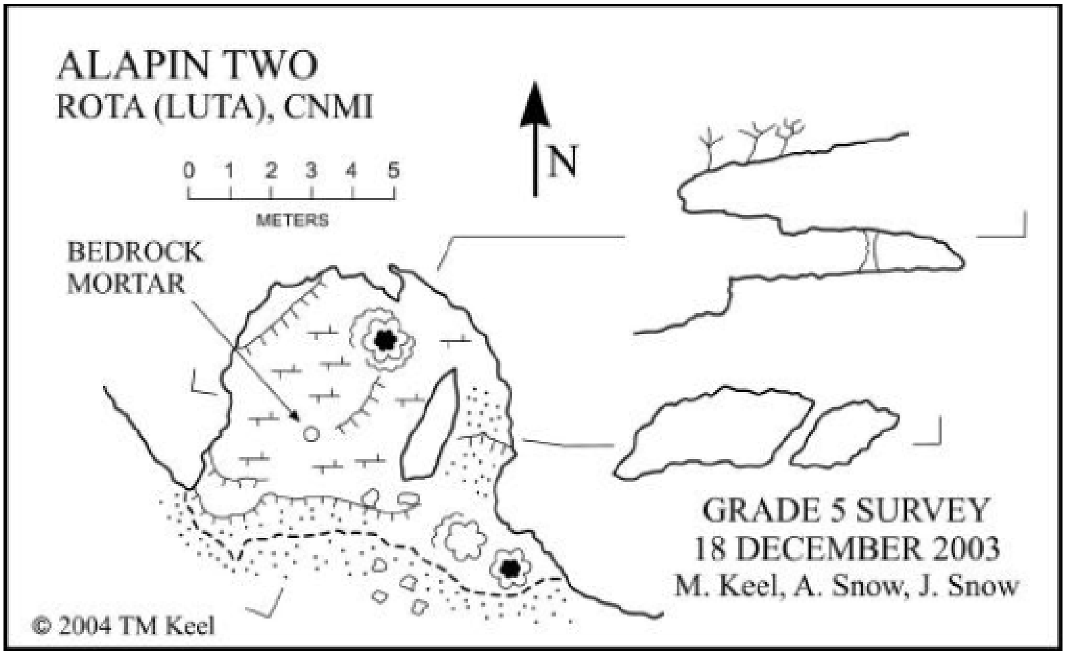

Figure 180: Map of Alapin Two

Arch Cave

Arch Cave is one of several caves along the coast between *Poña Point* and *Okgok*. The cave has two levels connected by a vertical hole. Each of the two levels has the appearance of a breached flank margin cave. Other caves in the area do not exhibit two-level development. The lower level consists of one low, wide "room" completely open on the south side. The upper level consists of an open "room" about 5 m high and about 20 m wide. It narrows to a small passage in the rear that leads to a chamber about 3 m wide and 2 m high.

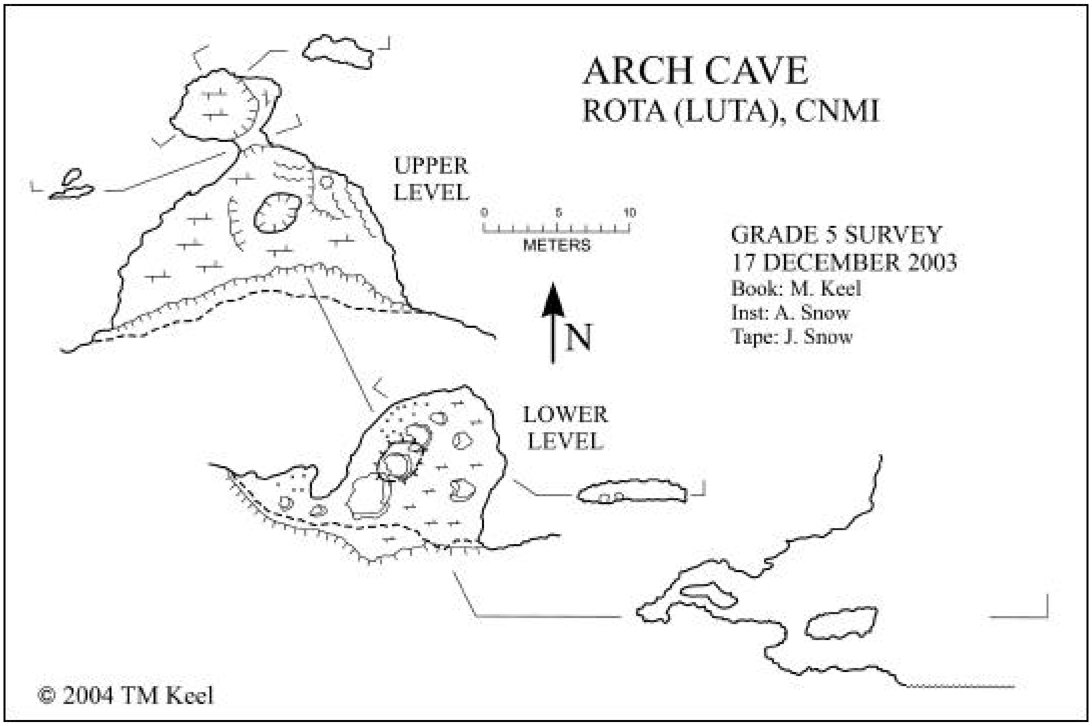

Figure 181: Map of Arch Cave

As Matan Cave

As Matan Cave is located at the about 350 m elevation, about 30 m east of Water Cave (*Matan Hanum*) on the *Talakhaya*. The 10 m wide by 7 m high entrance is reached by climbing up about 3 m from the base of the cliff at the limestone/volcanic contact. This climb is set back about 4 m inside the drip line. The contact is not exposed inside the cave. The cave consists of one room the width of which varies from 10 m at the entrance, to about 8 m in the middle and narrowing to a pinch out at the back, about 25 m from the drip line. Cross sections of the cave indicate that it is developed along the fracture visible in the ceiling. On the left side of the widest part of the cave are two small passages sloping downward through crumbly, incompetent, argillaceous limestone. These passages are very small and unstable and only extend a few meters.

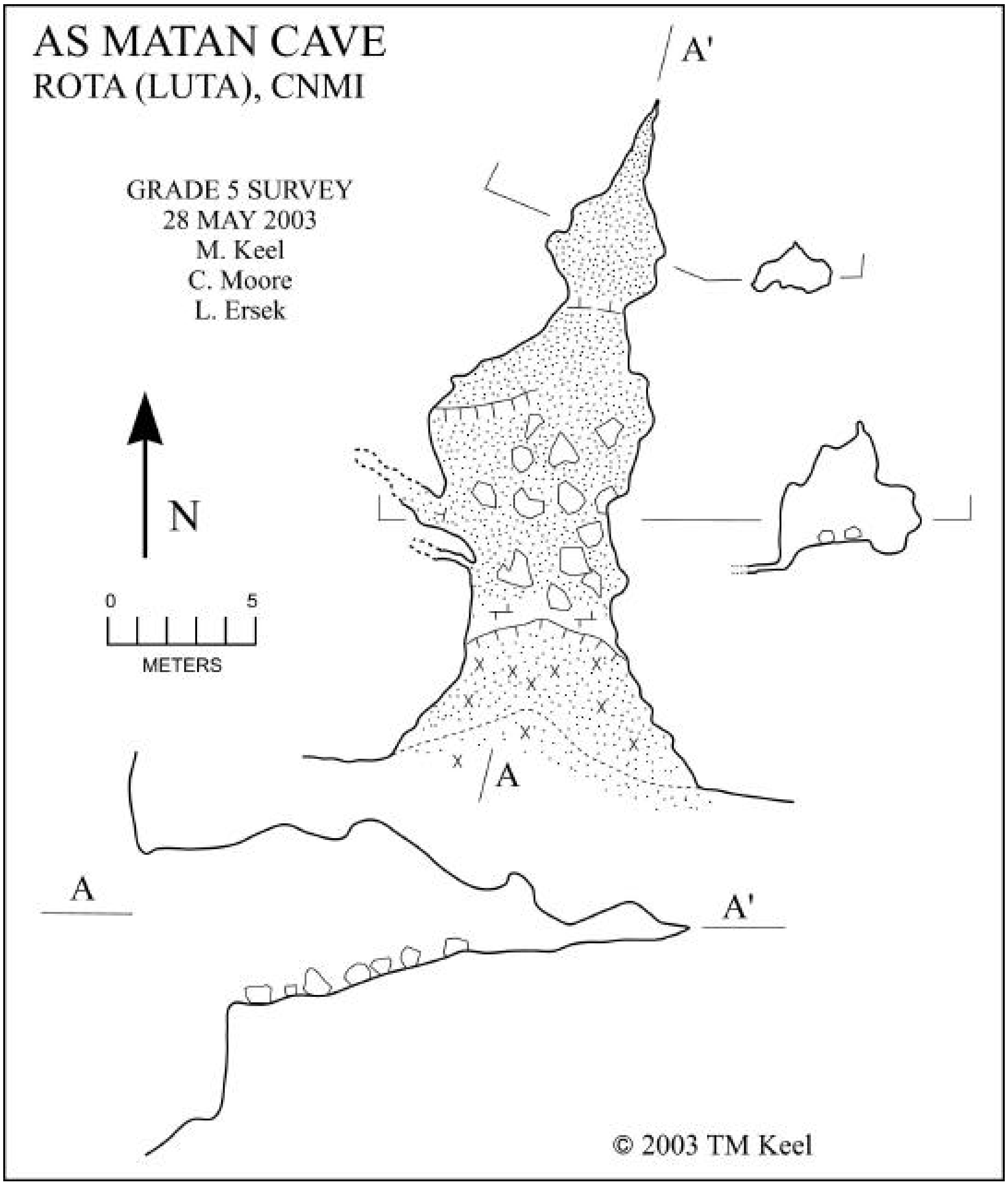

Figure 182: Map of As Matan Cave

Barbed Wire Cave

Barbed Wire Cave is one of several caves located along the base of the cliff next to the Water Cave Road at *Haofña*. The cave consists of one open chamber about 10 m long and 5 m high oriented north-south, and a small mostly enclosed room extending from the north end of the open chamber. The mostly enclosed room is apparently developed along a fracture.

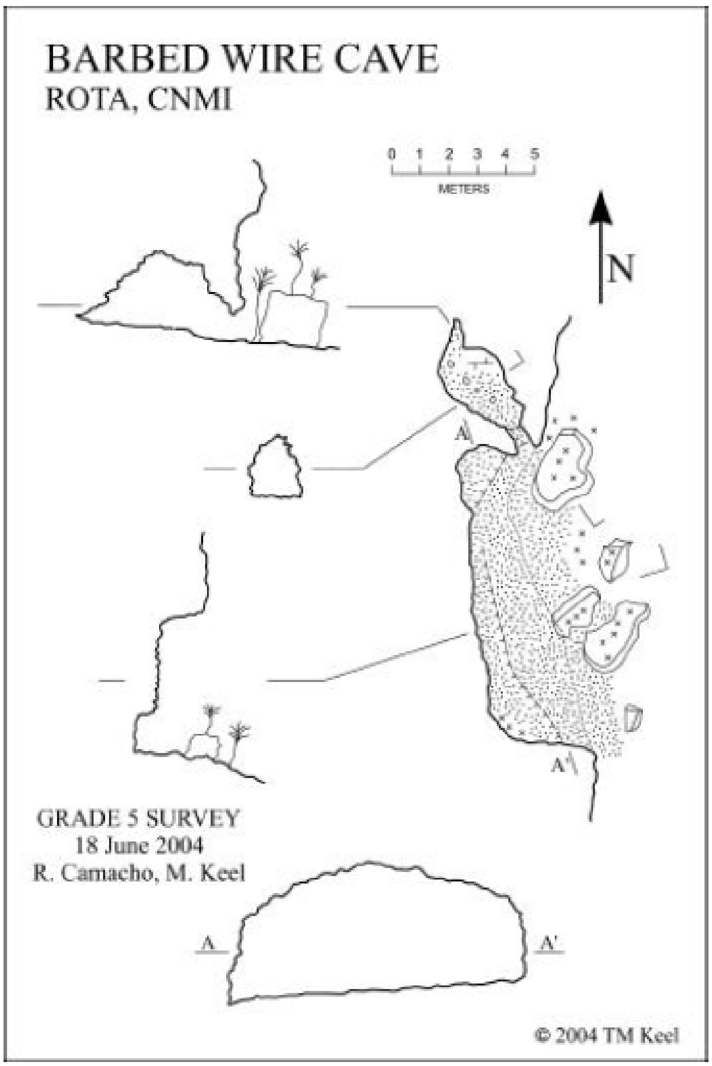

Figure 183: Map of Barbed Wire Cave

Bay Cave Remnant

Bay Cave is located south of the embayment at *Alaguan* Bay, in the 3 m bench along the coast. It consists primarily of an embayment in the cliff about 15 m by 25 m. The deepest point is about 4 m below the surrounding bench. The floor of the embayment has a series of 1 m bedrock ridges running parallel to the embayment. On the south side of the embayment is a section of cave that opens onto the embayment at both ends. The cave segment has an irregular cross section with maximum dimensions about 3 m by about 3 m. The passage is about 15 m long. Bay Cave Remnant appears to be the remnants of a flank margin cave.

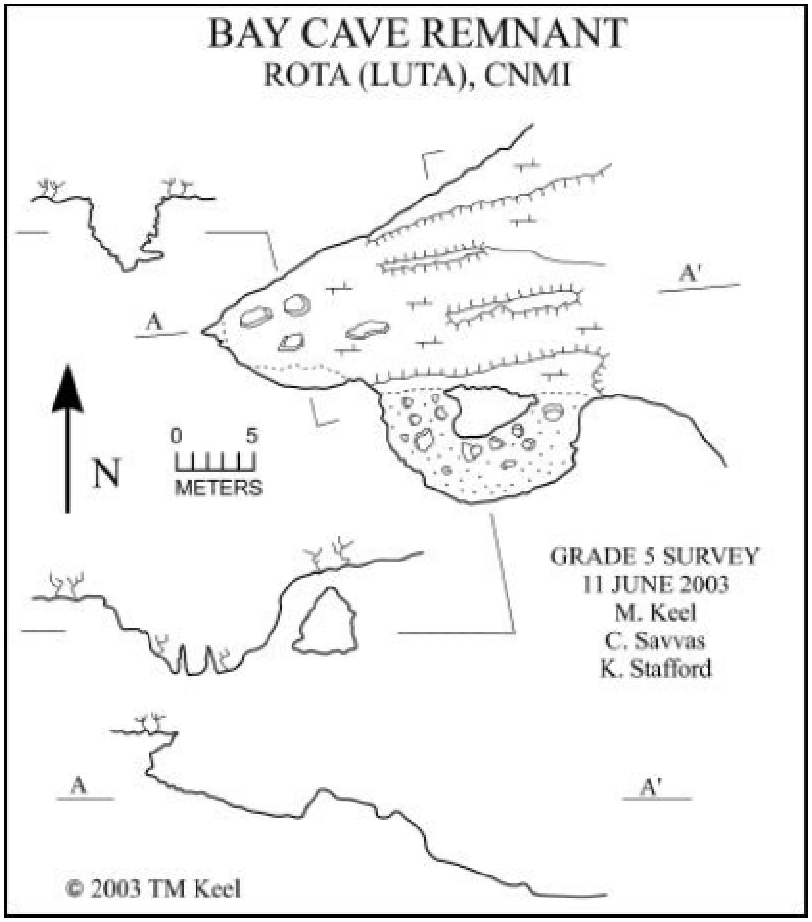

Figure 184: Map of Bay Cave Remnant

Breadfruit Cave

Breadfruit Cave is one of several caves located along the base of the cliff next to the Water Cave Road at *Haoña*. Breadfruit Cave consists of an overhang about 20 m long oriented north south. The overhang contains speleothems that indicate that Breadfruit is the remnant of a probable flank margin cave. Located about 0.5 m above the ceiling of Breadfruit Cave is a line of solutional holes each less than 1 m across, indicating a separate dissolutional horizon.

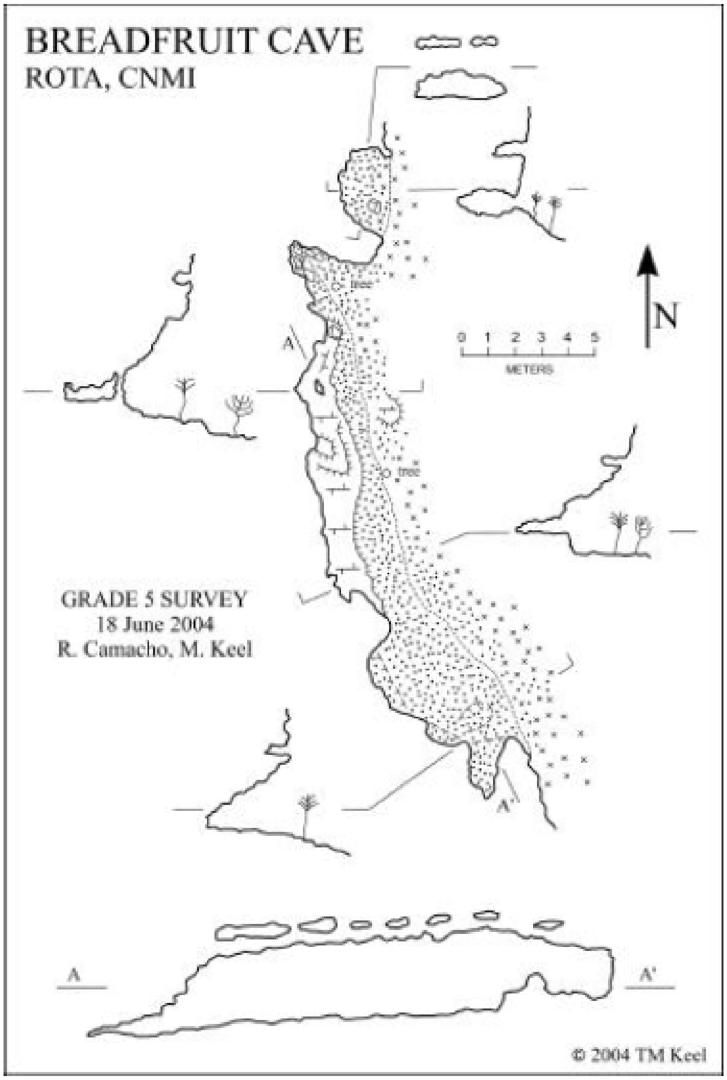

Figure 185: Map of Breadfruit Cave

Breccia Cave

Breccia Cave is located in south wall of the small cove on the west side of *Poña Point*. Breccia Cave consists of two sections; a large open overhang and a low wide cave section with two entrances. The overhang section of Breccia Cave is about 35 m long, oriented about 30° east of north. This section has partial enclosure at the north end. The overhang section of Breccia Cave is 8-9 m high at the north end and 2-3 m high at the south end. Exposed in the vertical back wall of the overhang section are poorly sorted to unsorted beds of un-lithified sand and gravel with clasts of various colors from off-white to brown to black, suggesting mixed lithology. There are also thin beds of brown clayey material. These beds are parallel to and interbedded with the adjacent limestone. The apparent mixed lithology beds and clays are interpreted as distal debris flow deposits. At the south end of the overhang section of Breccia Cave is a passage the leads to a room about 20 m long. The north end of this room is 1-1.5 m high, about 9 m wide and divided by a bedrock pillar. At the south end, the ceiling of this room rises in an irregular dome to about 4 m. In the center of this dome is a rough vertical shaft that extends up a total of about 9 m. On the west side of the dome is the other entrance to Breccia Cave.

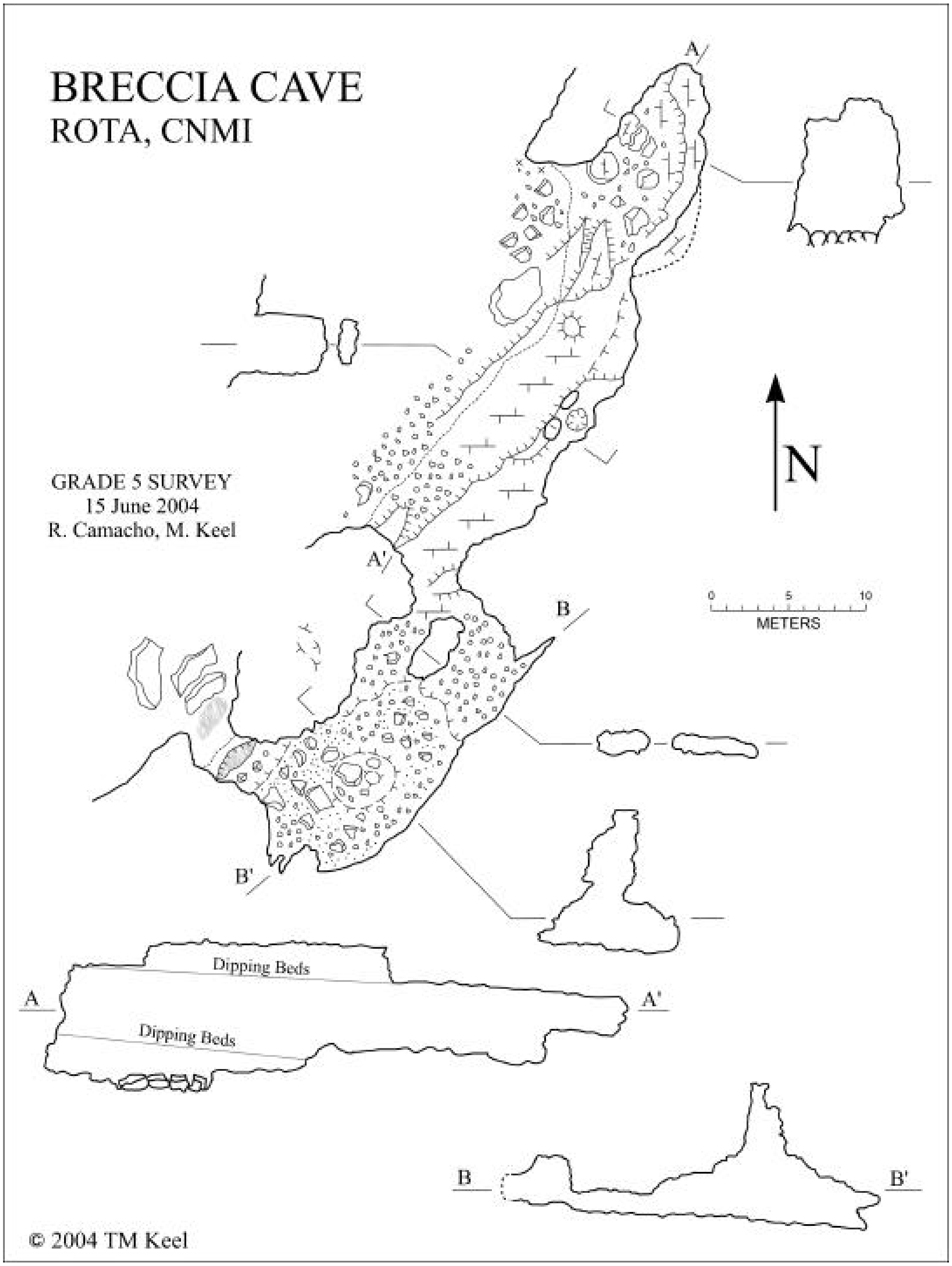

Figure 186: Map of Breccia Cave

Christmas Cave

Christmas Cave is located just inland from the west end of the beach at *Okgok*, where the main stream from the *Talakhaya* enters the ocean. The entrance to the cave is about 10 m wide and about 4 m high. The drip line merges with the inactive bio-erosion notch the runs along this cliff face. The cave extends back about 8 m from the drip line with the northern end of the cave being partially enclosed. The limestone in which Christmas Cave is developed exhibits dipping fore-reef beds.

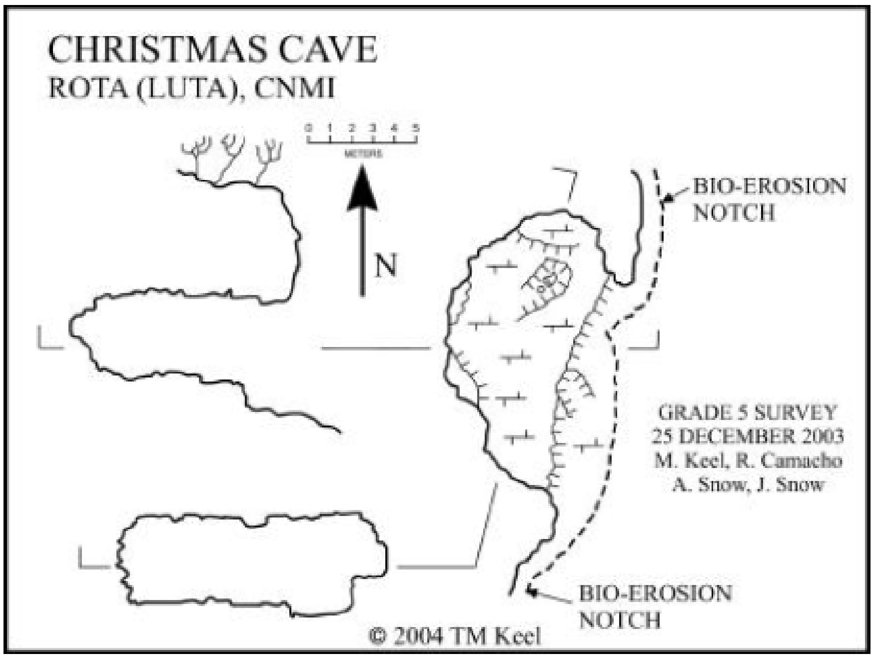

Figure 187: Map of Christmas Cave

Comet Cave

Comet Cave is one of several caves along the coast between *Poña Point* and *Okgok*. Two distinct parts of Comet Cave are encompassed by one drip line. The western, higher part consists only of a back wall, floor, and overhanging ceiling and appears to be a remnant of a flank margin cave. This part of the cave is about 1.5 m high, 5 m wide and 11 m long. The eastern, lower part of the cave is an open irregular chamber that appears to be developed along a fracture. It is about 10 m long, 3 m wide and 5 m high for most of its length. At the rear a small hole allows light to enter from above.

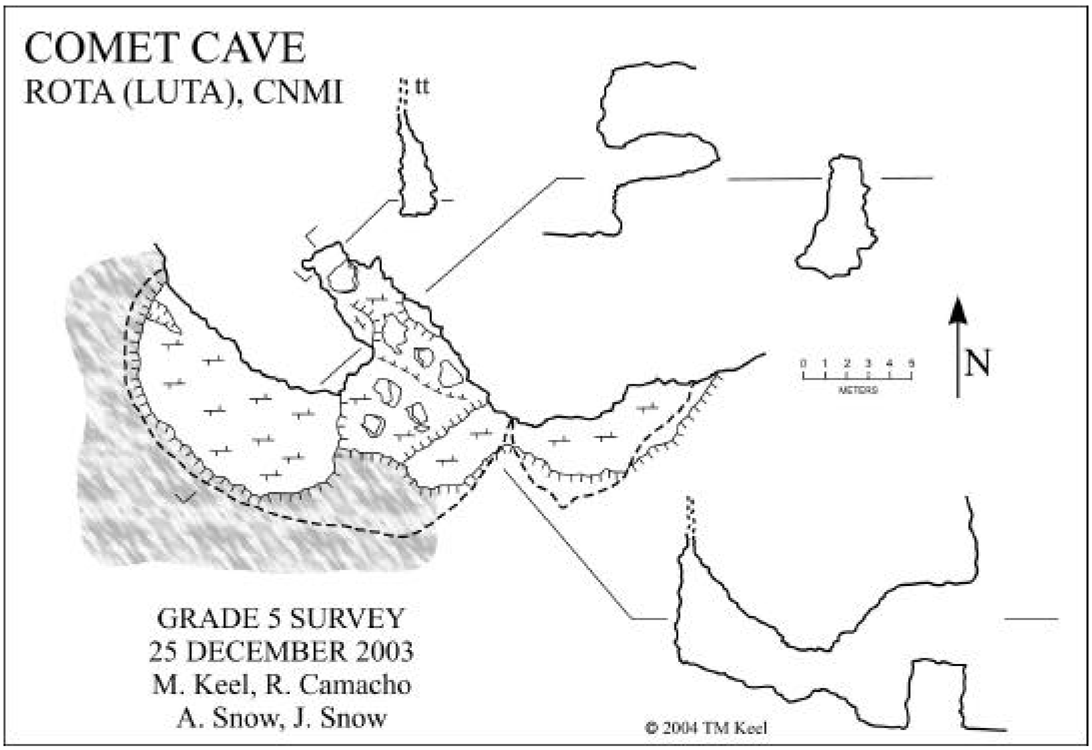

Figure 188: Map of Comet Cave

Compact Cave

Compact Cave is located at the base of the cliff below *I Koridot*. Compact Cave is about 15 m long, 2.5-3 m wide and oriented about 20 degrees east of north. The overall cross section of the cave is triangular. A small entrance opens near the south end of the cave, adjacent to three other holes that connect to the outside but are impassable. Compact cave appears to be the result of solutional modification of a detached bedrock slab.

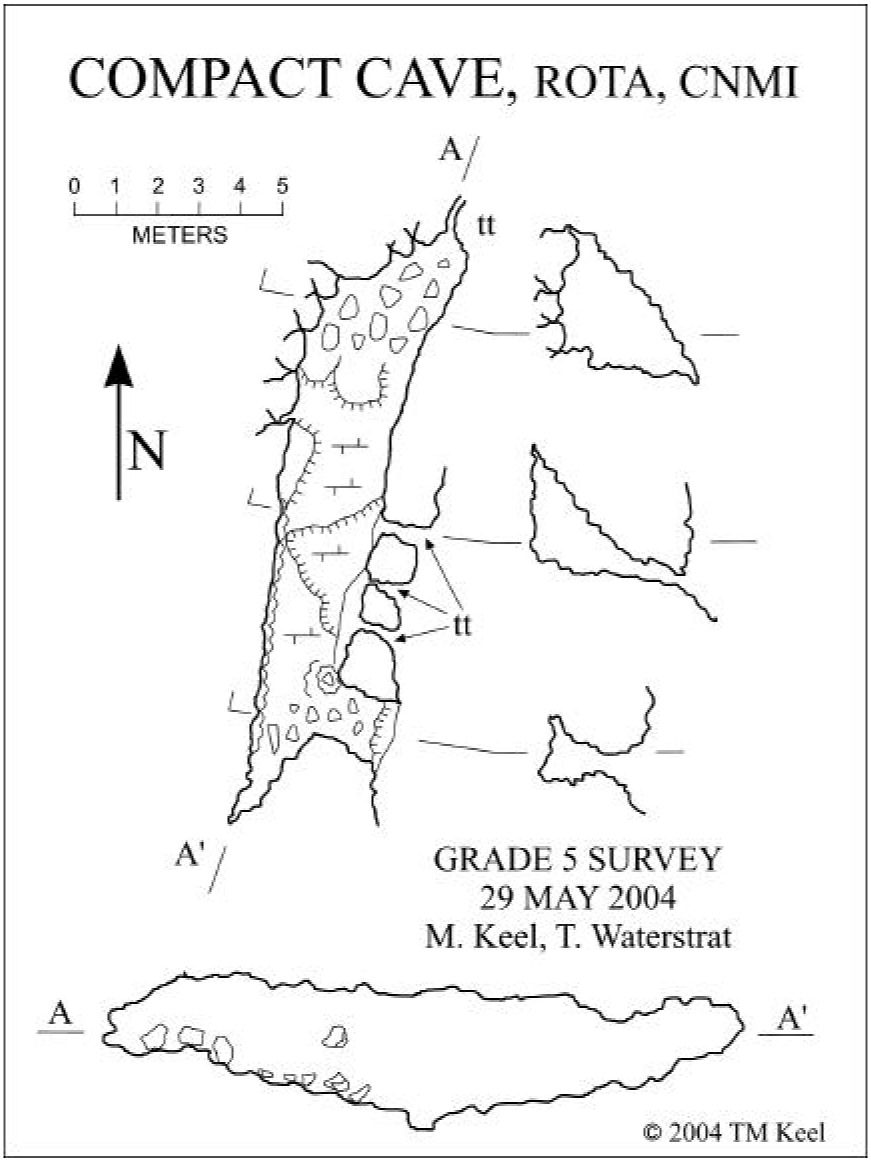

Figure 189: Map of Compact Cave

Crab Hunter Cave

Crab Hunter Cave is located at about 210 m elevation, about 20 m east of the road on the west side of the *Sabana*, near *Sailigai Hulo*. The cave consists of a main room about 7 m long and about 4 m wide open to the cliff face on the east side. From the south end of this room, a low passage leads up to an enclosed room about 4 m long and about 3 m wide. The cave is developed in a rubbly facies and clearly shows that the lithology of the fore-reef beds influenced the morphology. The floors of both rooms are parallel to the dipping beds.

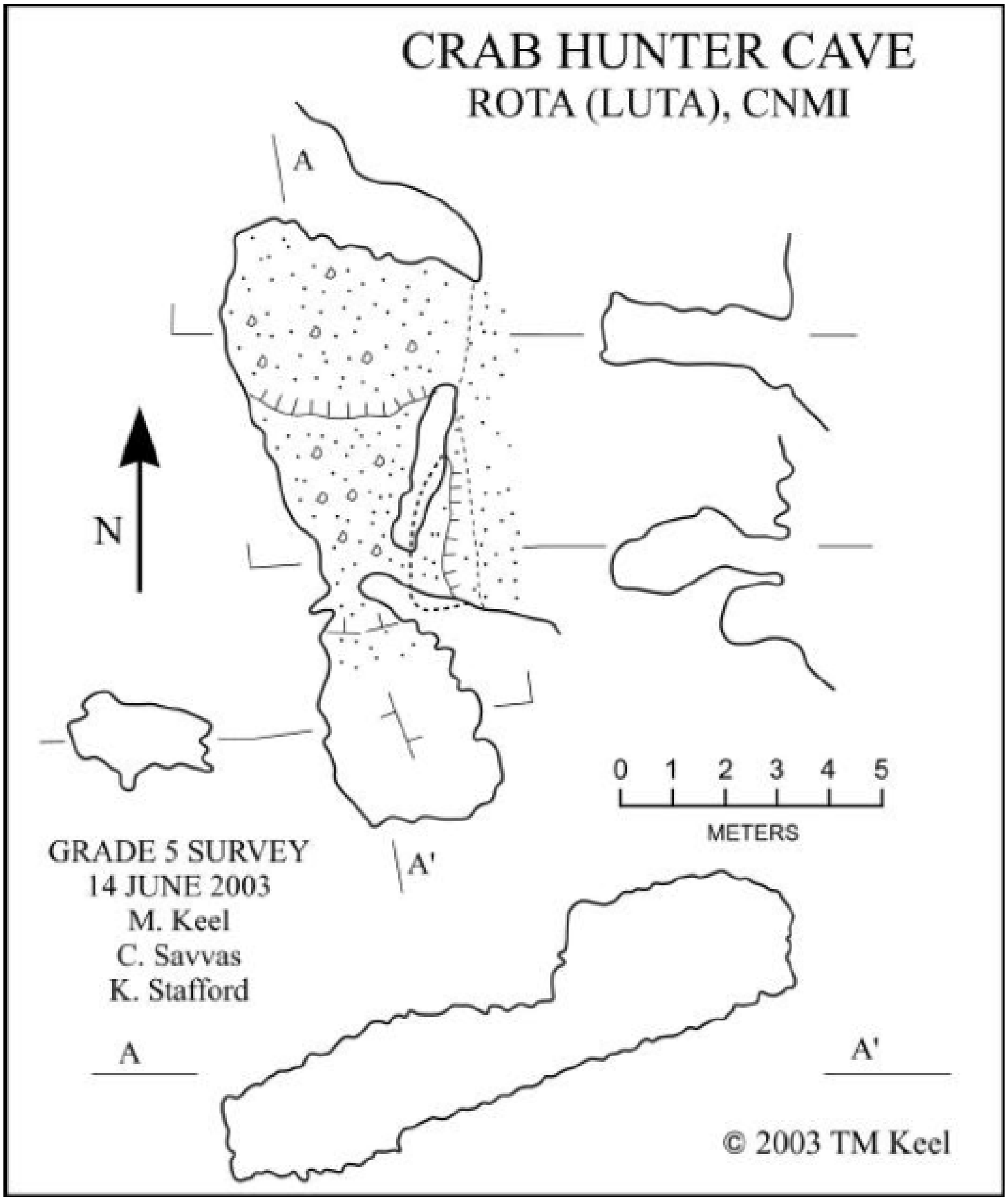

Figure 190: Map of Crab Hunter Cave

Cupid Cave

Cupid Cave is one of several caves along the coast between *Poña Point* and *Okgok*. The cave is developed along a fracture and extends about 8 m back from the drip line. The cave is variably 2-3 m wide and about 4 m high at the entrance. The floor and the ceiling of the cave slope up toward the back. There are two places where light penetrates from above through the crack along which the cave is developed. Cupid Cave is at the same level as the raised bio-erosion notch.

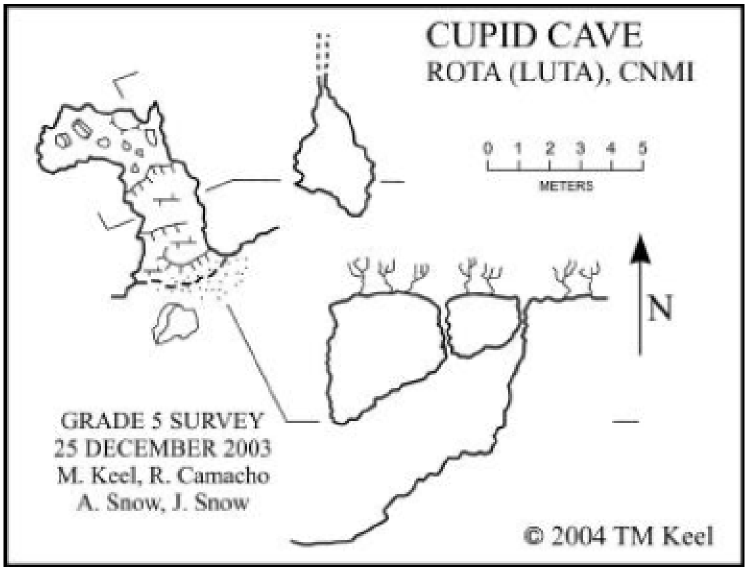

Figure 191: Map of Cupid Cave

Dancer Cave

Dancer Cave is one of several caves along the coast between *Poña Point* and *Okgok*. The cave consists of two small, open chambers, each about 3 m across, 2-3 m high and reaching about 4 m back from the drip line. Both parts of the cave are encompassed by the same drip line. Both chambers are above the level of the adjacent, active bio-erosion notch. This cave appears to have been significantly modified by physical erosion.

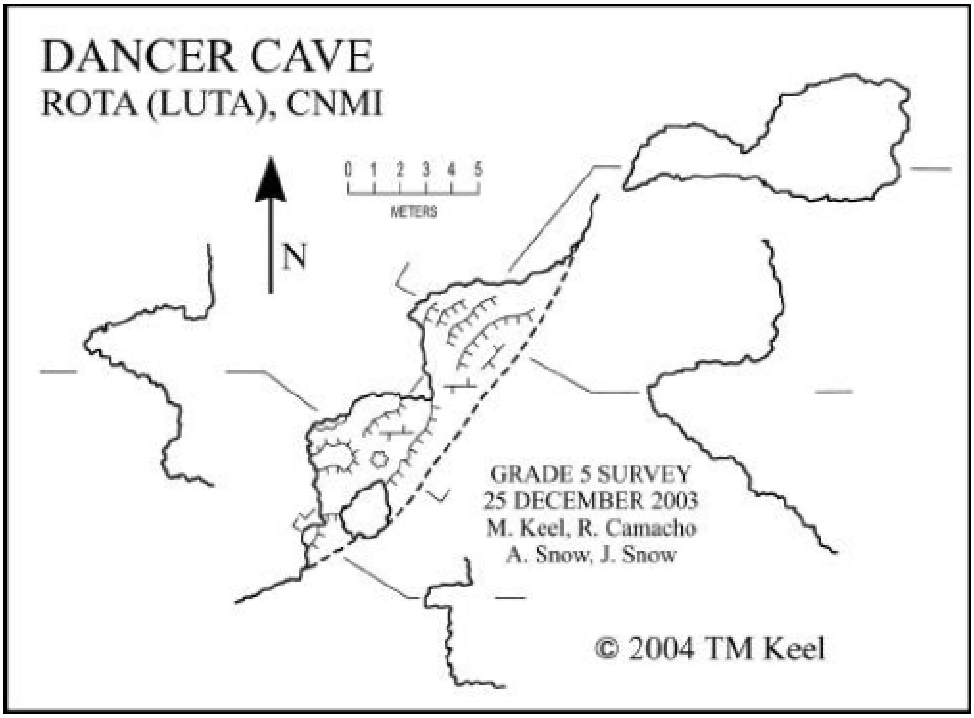

Figure 192: Map of Dancer Cave

Dasher Cave

Dasher Cave is one of several caves along the coast between *Poña Point* and *Okgok*. Dasher Cave consists of two remnant flank margin chambers encompassed by the same drip line. The sloping floors of these chambers are about 3 m above sea level.

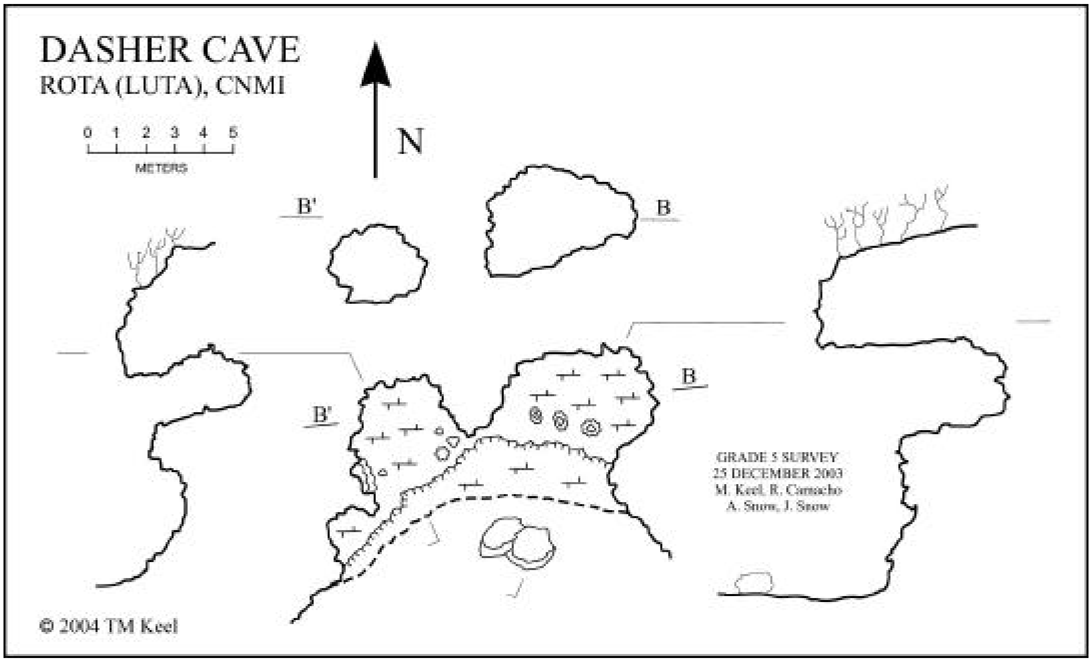

Figure 193: Map of Dasher Cave

Double Decker Cave

Double Decker Cave is located in the sea cliff just south of the lagoon below *Gagani.* Double Decker Cave is oriented northeast southwest. The upper section is about 33 m long, about 5-7 m high and extends about 9 m from the drip line. The large entrance to the upper section takes up the northern 2/3 of the northwest facing side of the cave and is visible from across *Sasanhaya* Bay at *Songsong* Village. The entrance to the lower section is behind a large boulder that is detached from the cliff just below the upper section. The lower section opens at sea level and is developed along a pair of linear fractures. The lower section extends for about 22 m to the southwest, where it narrows into the fracture. The ceiling in the lower section is 2-3 m high.

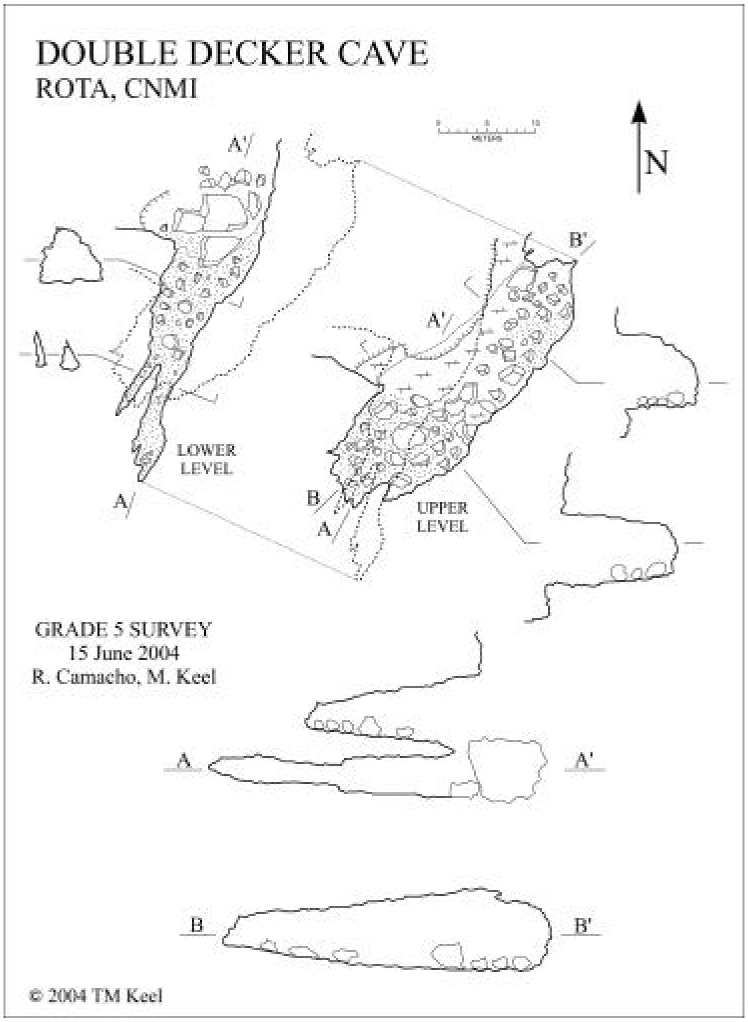

Figure 194: Map of Double Decker Cave

Grand Stand Cave

Grandstand cave is the largest cave overhang at *Tenetu* (*Teneto*), just east of *Songsong* Village. Grandstand Cave is in the cliff face immediately north of the site traditionally used for motocross racing during the Rota Fiesta. The cave is reached be a climb of about 4 m. Grandstand Cave is about 55 m long, 6-10 m high and 4-5 m.

Except for the northwest end, the cave is completely open. The outer wall of the northwest end is a series of large, closely space columns.

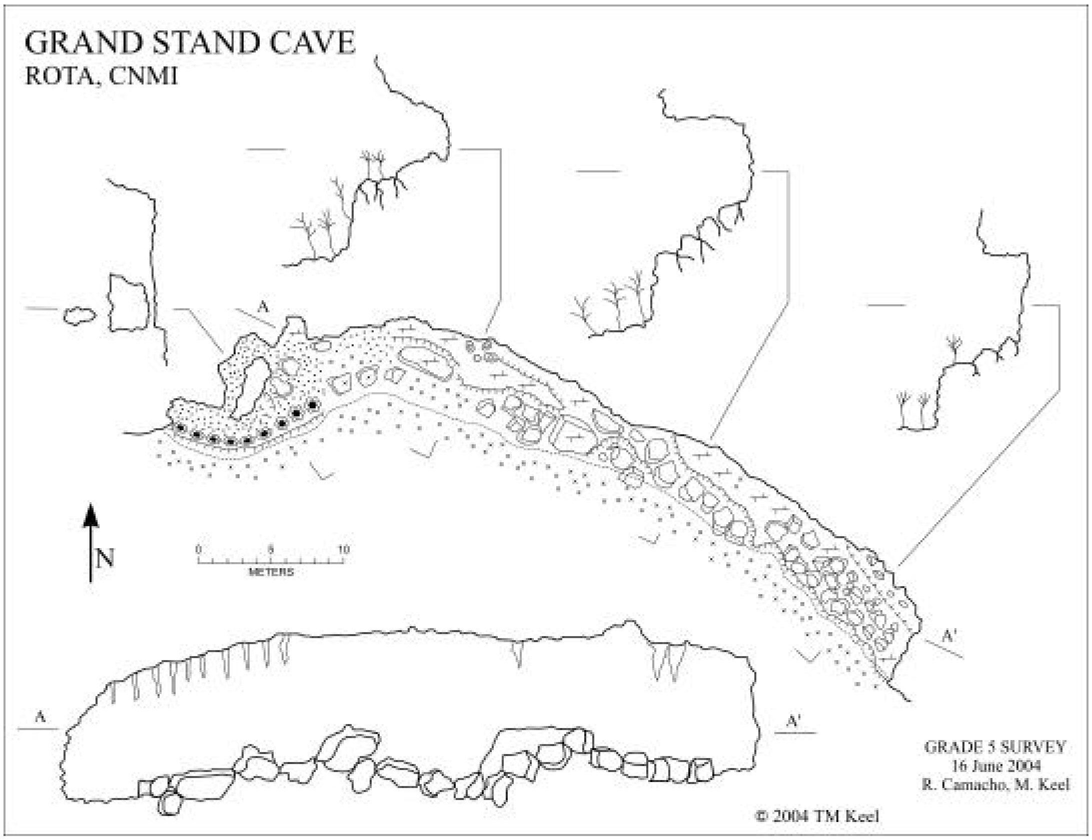

Figure 195: Map of Grand Stand Cave

Husky Cave

Husky Cave is located just south of *Liyang Matan* at *Puntan Fina Atkos* near *As Matmos* at about 25 m elevation at the base of the cliff. There is about 18 m of passage in this apparent flank margin cave. It is about 8 m wide just inside the entrance but narrows to about 1.5 m before ending in a boulder wall. The floor of the outer part of the cave is covered with what appears to be beach sand.

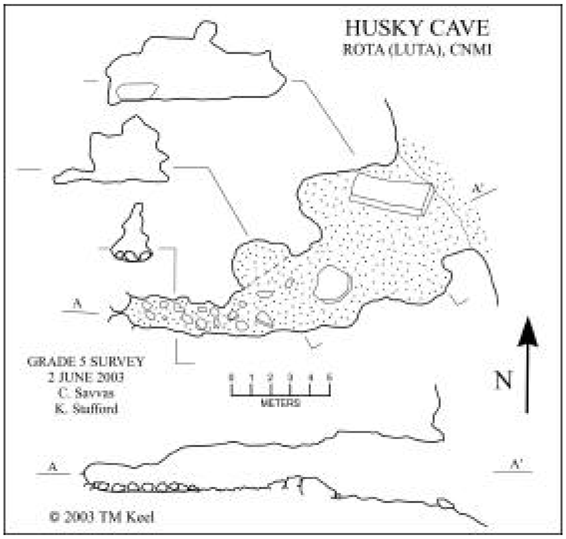

Figure 196: Map of Husky Cave

I'm Your Cistern Cave

I'm Your Cistern Cave is located in the cliff face at *Tachok*, east of *Songsong* Village. The cave is one of many visible from the main road and is reached by climbing about 4 m up the cliff face. The side of the cave open to the cliff face is about 15 m across while the cave has a maximum width of about 12 m. The floor is irregularly sloped to the edge of the opening and mostly covered with loose boulders, cobbles and sand. There are some speleothems along the back wall. I'm Your Cistern Cave is apparently a remnant of a flank margin cave.

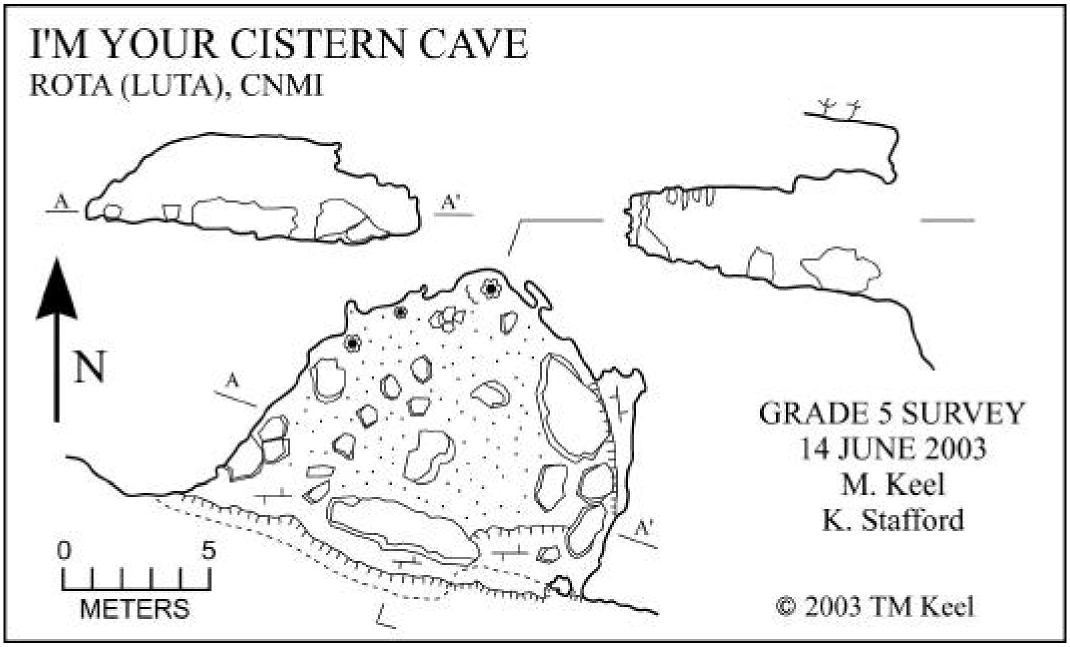

Figure 197: Map of I'm Your Cistern Cave

Itsy Cave

Itsy Cave is located south of the embayment at *Alaguan* Bay, about 30 m down-slope from the entrance to Deer Cave. Isty Cave consists only of a curved tube about 1 m in diameter and about 3 m long. It is apparently a remnant of a flank margin cave. *Kaigun* 223 Japanese Command Post Although this site contains no real caves, *Kaigun* 223 Japanese Command Post is documented here as an example of the World War II era tunnels that are common on Rota. It is located in the northeast facing cliff at *Ginalangan* at about 240 m elevation, south of the white crosses prominently visible in the same cliff face (Four Crosses). This site has extensive human modification including at least four pillboxes, three cisterns, a defensive wall running about 160 m, and several man-made tunnels most of which have barrier walls at their openings.

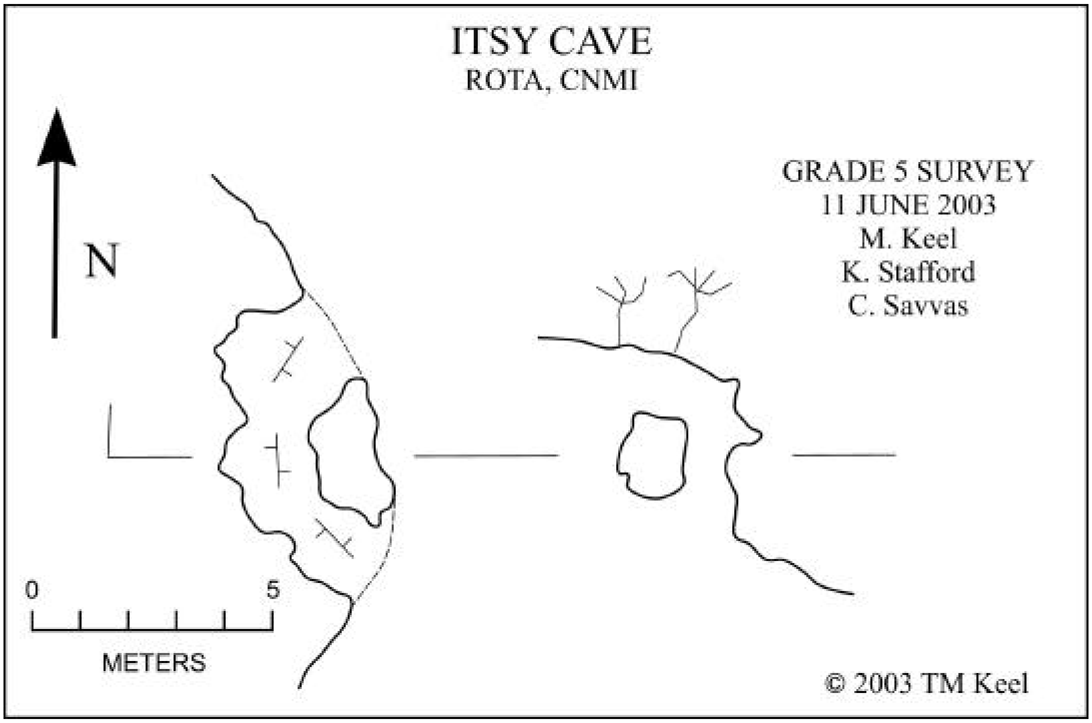

Figure 198: Map of Itsy Cave

Misplaced Cave

Misplaced Cave is located at the base of the cliff just inland from the coast, northeast of *Puntan Malilok* and is developed in a very bouldery facies. The entrance to Misplace Cave faces southeast and is about 9 m across. Misplaced Cave extends back about 10 m over a floor that is mostly loose soil with some cobbles. The cave is about 2.5 m high for most of its length.

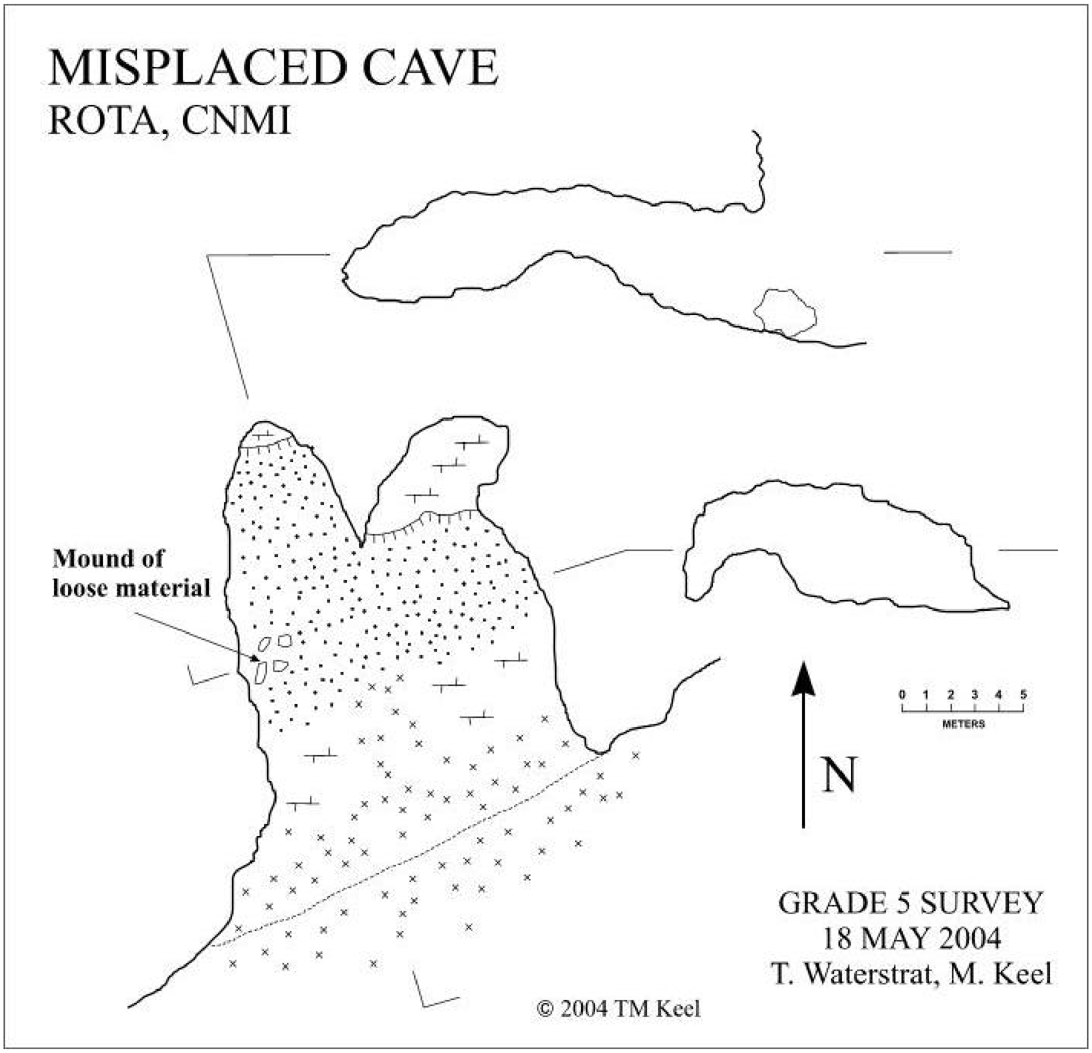

Figure 199: Map of Misplaced Cave

Picnic Cave

Picnic Cave is a flank margin cave located just above sea level, beside the main road, at the coastal notch adjacent to *Puntan Sailigai*. The cave is located inside a knob of limestone projecting higher than the general trend along this immediate section of coast. The oval main chamber of Picnic Cave is about 18 m wide and extends back about 13 m back from the drip line and has an entrance about 10 m wide. This main chamber is variably about 2 m high and floored with loose beach sand plus a few cobble, boulders and abundant storm debris. To the east of the main entrance is a 10 m long overhang, encompassed by the same drip line that has the appearance of a bio-erosion notch. Off the west end of the main chamber is a smaller room also floored with beach sand, etc. To the west of the main chamber there are two open cave sections encompassed by the same drip line. The easternmost of these sections has a small connection to the side room off the main chamber. Just outside this part of the cave is a large (6 m long and 3 m high) limestone boulder that may be a breakdown block from above the cave or may be in place bedrock.

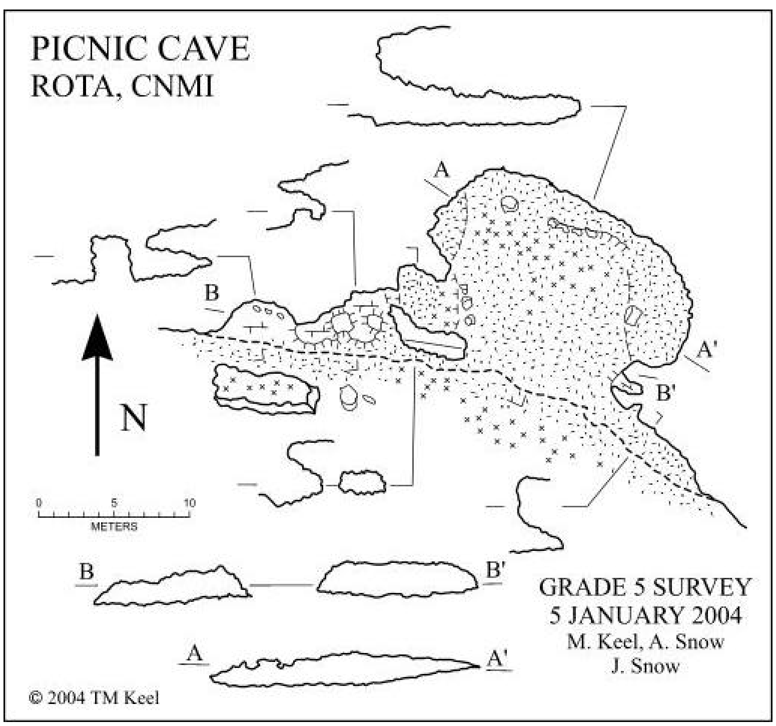

Figure 200: Map of Picnic Cave

Pie Cave

Pie Cave is one of several caves along the Water Cave Road near *Haofña*, near the "cave" symbol on the USGS topographical map (1999). Pie Cave opens to the south and is about 11 m long and 7 m wide. The cave consists of one low, steeply sloping chamber less than 1 m high. The drip line of the Pie Cave coincides with what appears to be a bioerosion notch.

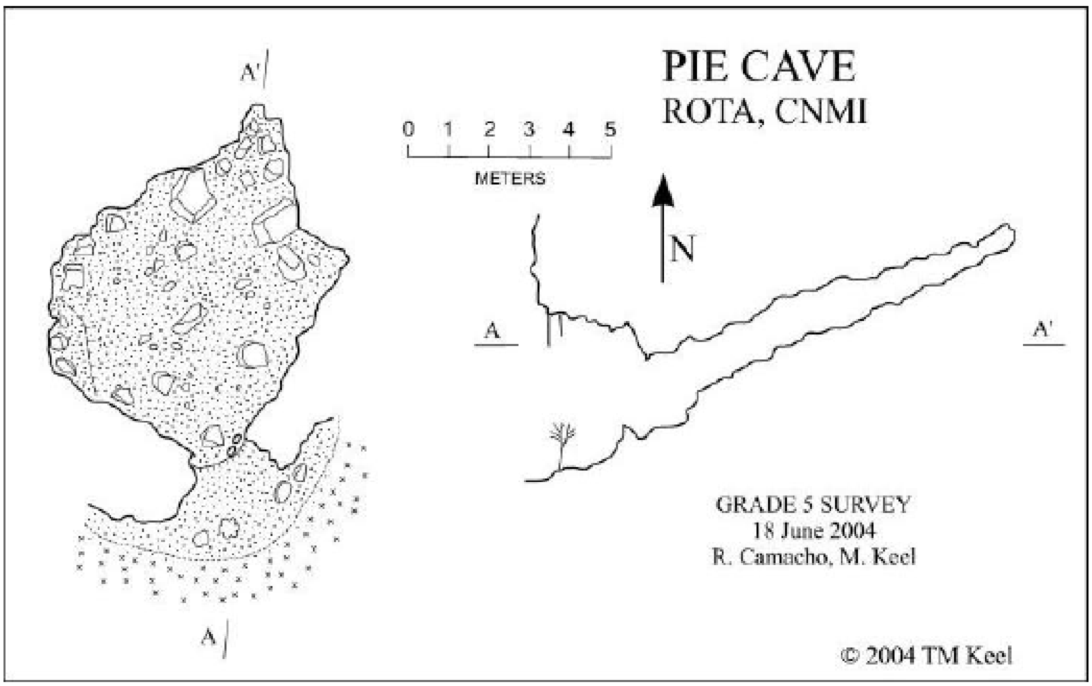

Figure 201: Map of Pie Cave

Prancer Cave

Prancer Cave is one of several caves along the coast between *Poña Point* and *Okgok*. Prancer Cave is about 8 m wide at the drip line and extends back about 10 m with a small 2 m extension at the back. Beyond the drip line, the cave widens to about 9

m. The cave ceiling is about 5 m at the drip line but drops steeply to about 3 m. The ceiling climbs toward the back of the cave at about the same slope as the floor. The floor of the cave mostly covered with boulders that in some places are covered with soil that comes into the cave through fractures that lead up to the surface.

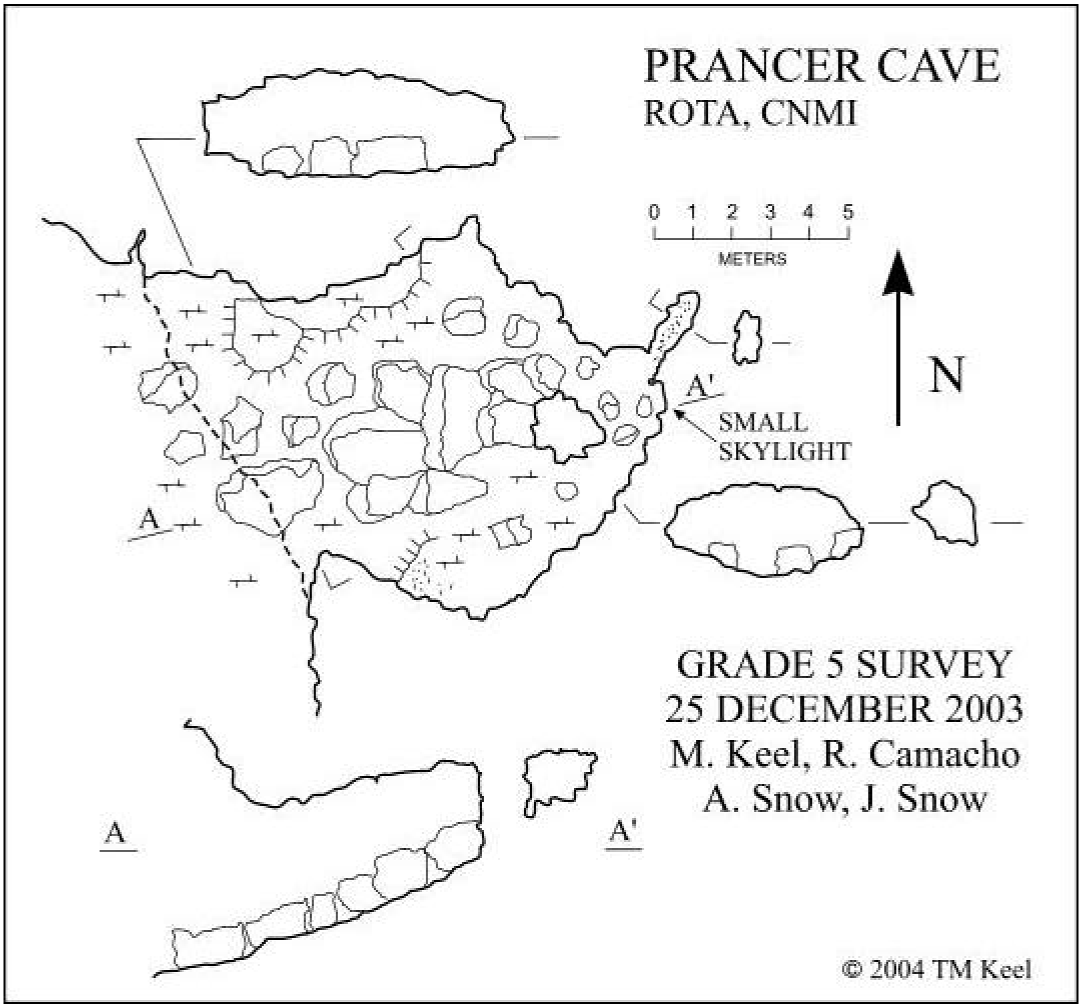

Figure 202: Map of Prancer Cave

Sagua Cave Complex

The *Sagua* Cave Complex is located at sea level below *Sagua*, about 2 km southeast of *Songsong* Village. The complex consists of about 650 m of coastal cliff line that contains numerous, breached, erosionally modified, flank margin caves that required 1168 m of survey to document. Assigning a specific number to the caves in this complex is problematic because many are connected through small holes and many share the same drip line. This complex was mapped as one unit in order to show the very high density of cave development. Significant fresh water discharge was noted at sea level in several places along this stretch of cliff line in May 2003. In January 2004 some of these locations had very large fresh water discharges; detectable by temperature difference and by schlieren mixing for tens of meters out into the ocean. The northernmost end of the complex is located in the cliff face behind the only "mushroom" shaped sea stack along the coast at *Sagua*. Here, there is a small cave about 3 m long. About 4 m to the south there is a 5 m long section of cave containing an arch. The floor of this section is a compact, fine-grained facies but the walls and ceiling are in a boulder/cobble conglomerate. About 10 m further south there is a large section of cave with typical flank margin cave morphology. The floor here is the same compact fine-grained limestone; the walls and ceiling expose the boulder/cobble conglomerate with some boulders up to 2-3 m maximum dimension. This section of cave has some secondary speleothems, including soda straws and some small phototrophic stalactites. Just south of this section, the cliff line extends out to the high tide line, but a partially collapsed cave section allows easy passage. There is "boneyard" development in this section. From here, there is continuous flank margin cave at the level of the elevated bio-erosion notch; about 2 m. The same contrast between the fine-grained limestone on the floor and the boulder/cobble conglomerate exposed in the walls and ceilings is prominent in this section as well. This section of cave ends where a large, in-place conglomerate boulder extends out to the high tide line. Just south of this boulder, there is a small linear cave at about 2 m elevation, apparently developed along a fracture and exhibiting sculpted wall morphology suggesting that is once acted as a discharge conduit for fresh water. This cave is about 8 m long and extends vertically as a small crack for 3-4 m. Just south of this linear cave there is a breached flank margin cave that extends back about 7 m. To the south of this cave, there is a break in cave development for about 25 m of cliff line. This section of cliff has a very well developed elevated bio-erosion notch and several fractures discharging fresh water. The next cave to the south appears to be a breached flank margin cave that extends back about 5 m from the cliff face. Just south of this, there is a breached flank margin cave about 4 m across that has a large skylight formed by ceiling collapse. Sea level fractures here appear to be discharging fresh water. For the next 16-17 m of cliff line there is no cave development, but there is a fracture discharging significant volume fresh water at sea level. This discharge was easily detectable by schlieren mixing even with tide fairly high. About 4 m south of this spring, the cliff face turns inland behind some large (4 m) boulders. In the corner, where the cliff face turns back toward the south, there is a fragment of what appears to be flank margin cave. This area has several large masses of weathered flowstone, supporting the idea that it is a collapsed cave. The next cave appears to be a small collapsed flank margin cave. South of this there is a 6 m section of broken cliff line set back from the flat bench above the present bio-erosion notch. There is a small flank margin remnant at the south end of this section. Just a few meters to the south is the most complicated section of the *Sagua* Cave Complex. It is a flank margin cave about 7 m by 7 m, breached on the north and south, and closed on the seaward side. The complication of this section is due to the many remnant pillars of bedrock scattered though the cave. South of this section, there is a section of cliff face about 8 m high that has a small cave at about 4 m elevation that runs parallel to the cliff face and has entrances at the north and south ends. Just to the south, there is the largest notch in the cliff line along this section of coast. The opening to this notch has several large (5-6 m) boulders. The notch extends back about 20 m from the high tide line to a relatively small overhanging cave remnant in the back. The north wall of this notch has the facies change contact from the lower, finer-grained limestone to the upper, boulder/cobble conglomerate at about 7 m elevation. The south wall of the notch has the same contact at about 9 m elevation, suggesting that the notch is developed along a normal fault. It is impossible to clearly see the relationship of the north and south sides of the contact where the two cliff faces meet in the overhanging cave. The section of cliff face just south of this notch is riddled with "boneyard" cave development. The next two sections of cave to the south, extend below sea level and area receive direct wave action. The larger of the two is a partially enclosed cave and is a popular swimming hole. Beginning adjacent to this cave and extending to the south there is a level bench up to 4 m wide at sea level. At the south end of this bench there is a manmade stone wall about 1 m high.

On the cliff face above the wall there is a concrete foundation that was part of the Japanese era facility for moving processed phosphate onto ships at *Sagua* (Rodgers, 1948). The approximately 70 m of cliff line between the remains of the tram tower foundation and the rocky beach contains several small flank margin cave remnants at sea level. The *Sagua* Cave Complex is an outstanding example of flank margin cave development. There is evidence that the exact elevation of cave development may have been locally driven by the position of the contact between the lower finer-grained limestone and the upper boulder/cobble conglomerate. Also, the apparently offset in the elevation of the contact between these two facies, in the large notch in the central part of the complex, suggests that there may be a normal fault through this area.

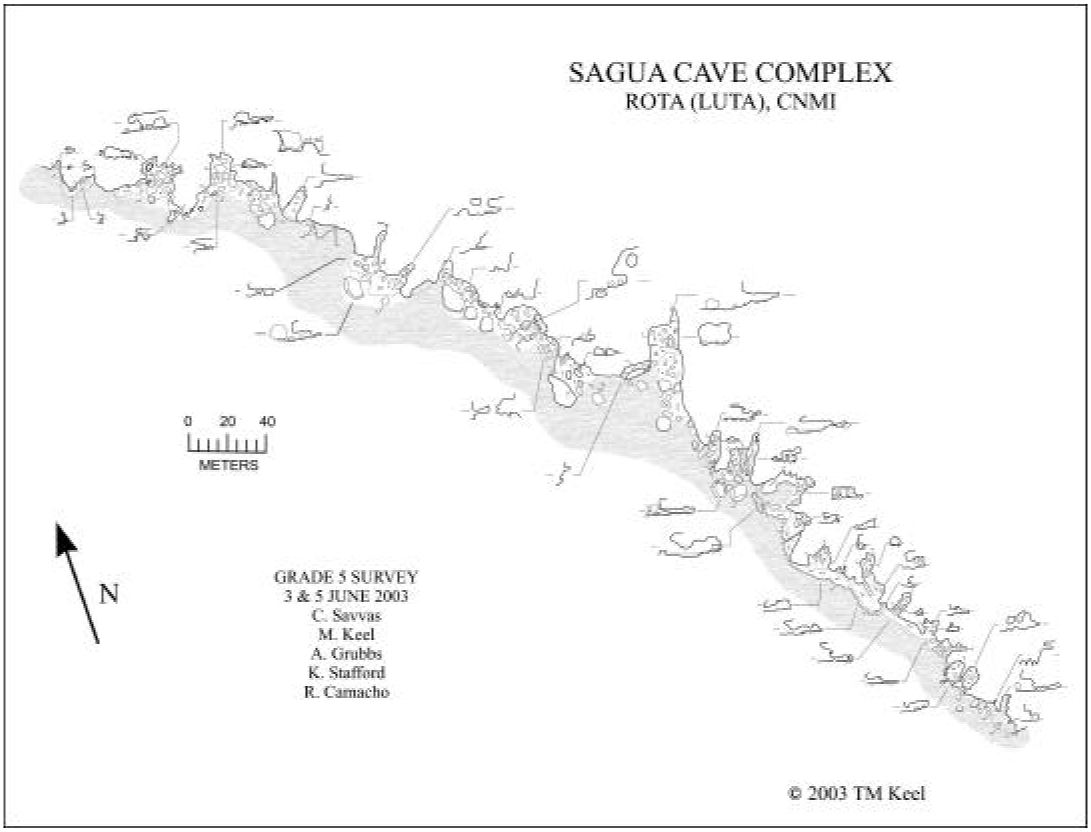

Figure 203: Map of Sagua Cave Complex

Saguita Cave

Saguita Cave is located at sea level, just west of *Sagua* Cave Complex, below *Takta*. It is apparently a breached, erosionally modified flank margin cave. Some parts of the cave are developed in boulder facies and in one area the cave

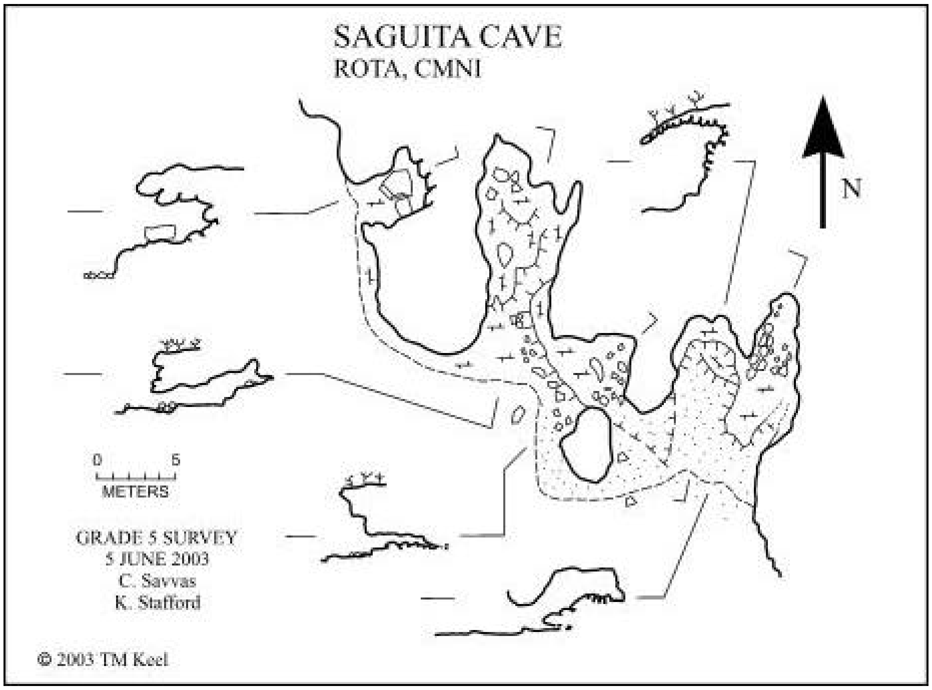

Figure 204: Map of Saguita Cave

Sea Stack Cave

Sea Stack Cave is at about 20 m elevation, about half way between *Tachok* and *Takta*, inland from the houses along the road. The entrance to Sea Stack Cave is in the bioerosion notch in an apparent former sea stack. The cave is a 6 m long chamber less than 1 m high, reached by an entrance facing east. The outer part of Sea Stack Cave shows evidence of ancient human occupation.

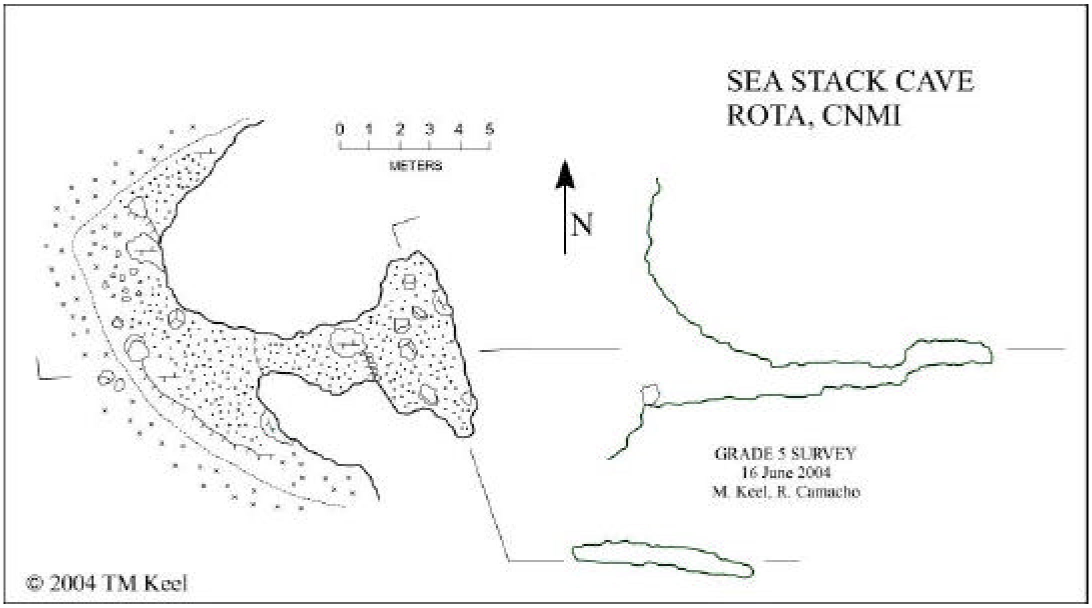

Figure 205: Map of Sea Stack Cave

Shoo Fly Cave

Shoo Fly cave is located at *Taiapu* on the east end of the *Talakhaya*, just north of the road, at about 140 m elevation. It consists of three flank margin remnants at the base of the cliff. The easternmost section is about 17 m long, 2 m high and 3 m deep and floored with sand. The middle section is 10 m long, 3 m deep, with a ceiling the tapers up into the cliff face and a bed rock floor. The westernmost section is 10 m long, 7 m deep, and 7 m high with a floor mostly covered with sand. Fore-reef beds are well expressed in all three sections.

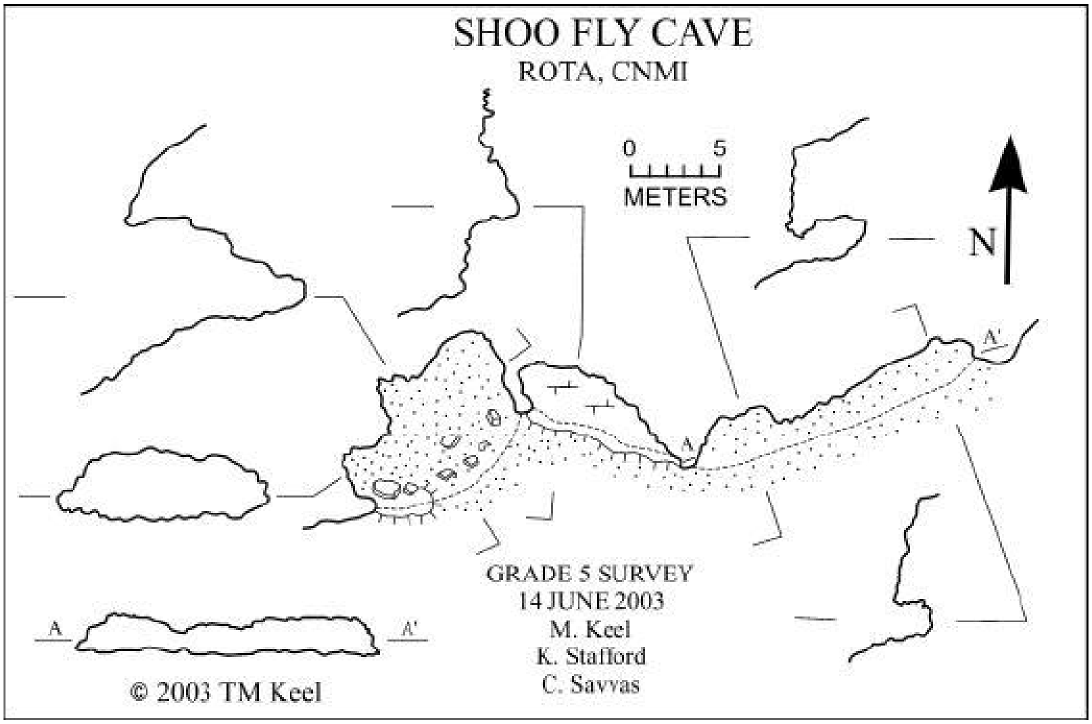

Figure 206: Map of Shoo Fly Cave

Stacked Wall Cave

Stacked Wall Cave is one of several caves along the Water Cave Road near *Haofña*. The cave consists of one dirt-floored chamber about 12 m east west and about 9 m north south. The ceiling is about is 3-4 m high except for a dome on the west side that reaches about 5 m. The most distinctive features of Stacked Wall Cave are the fore reef beds eroded out in relief and the 4 m long 1.5 m high dry-laid stone wall the spans most of the cave entrance.

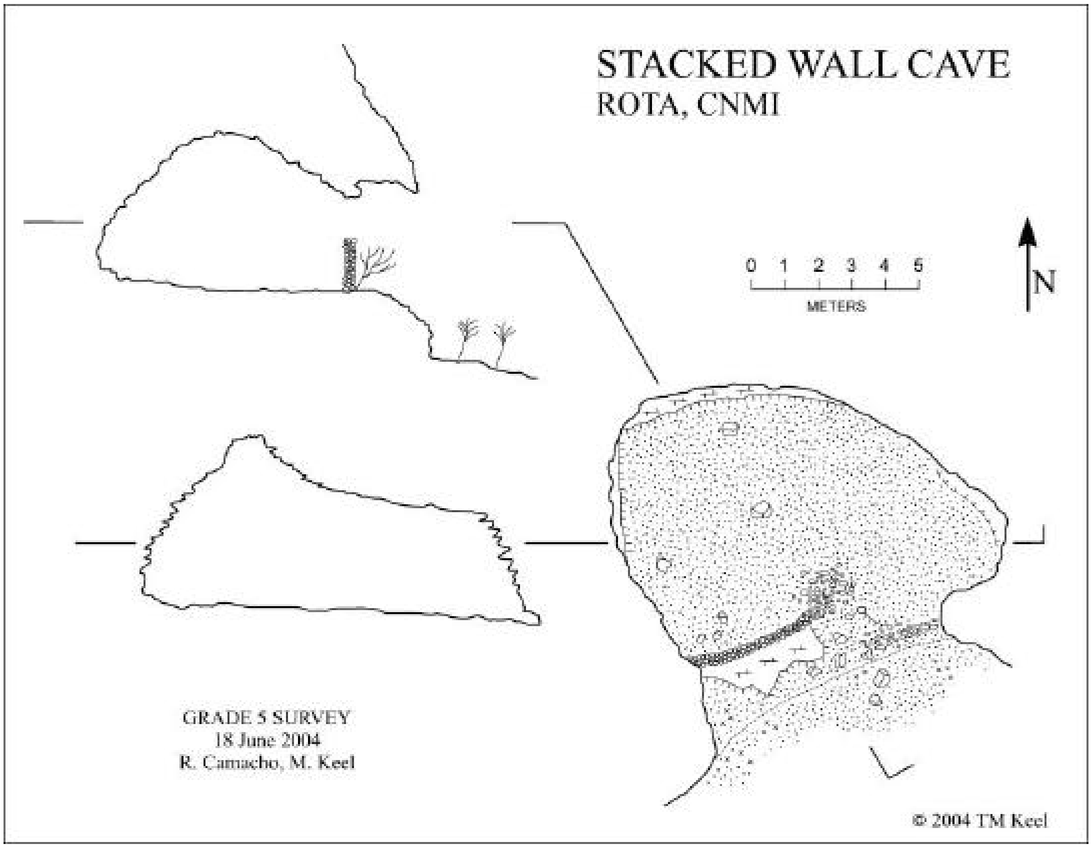

Figure 207: Map of Stacked Wall Cave

Tree Top Cave

There was no description provided for this flank margin cave.

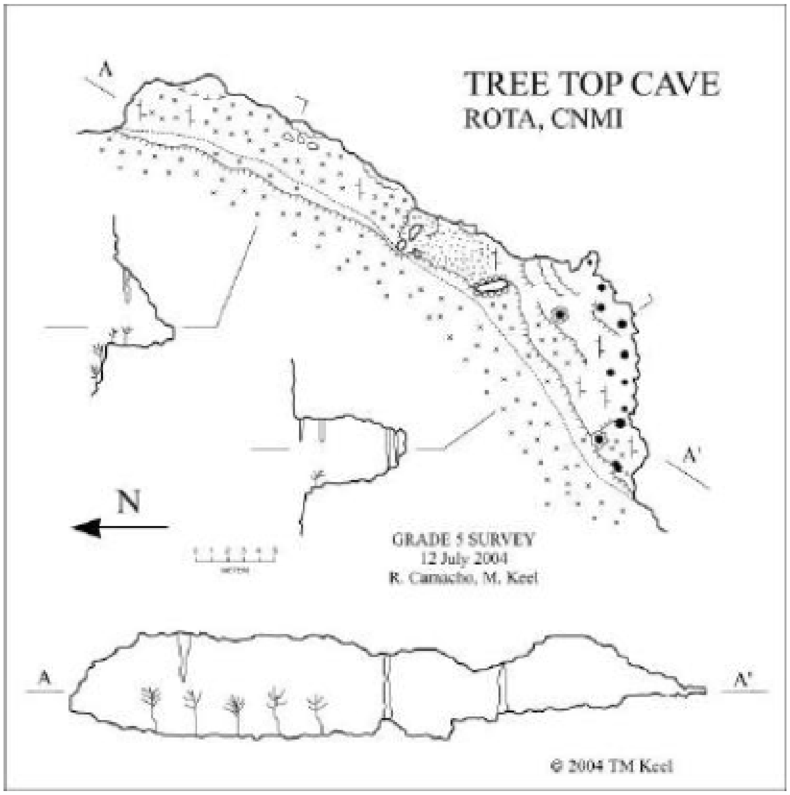

Figure 208: Map of Tree Top Cave

Vixen Cave

Vixen Cave is one of several caves along the coast between *Poña Point* and *Okgok*. The entrance to Vixen Cave is dominated by a boulder about 4 m high that contacts the drip line dividing the entrance into two parts. The cave extends back about 8 m from this boulder. The floor rises irregularly and the ceiling drops to make the rear of the cave about 1 m high. The boulder-strewn floor of the cave also slopes steeply to the south, probably reflecting fore-reef beds. Vixen Cave is about 9 m wide at the entrance and gradually narrows toward the back. The shape of Vixen cave suggests that it may have had a flank margin origin, but modification by physical erosion makes a determination difficult.

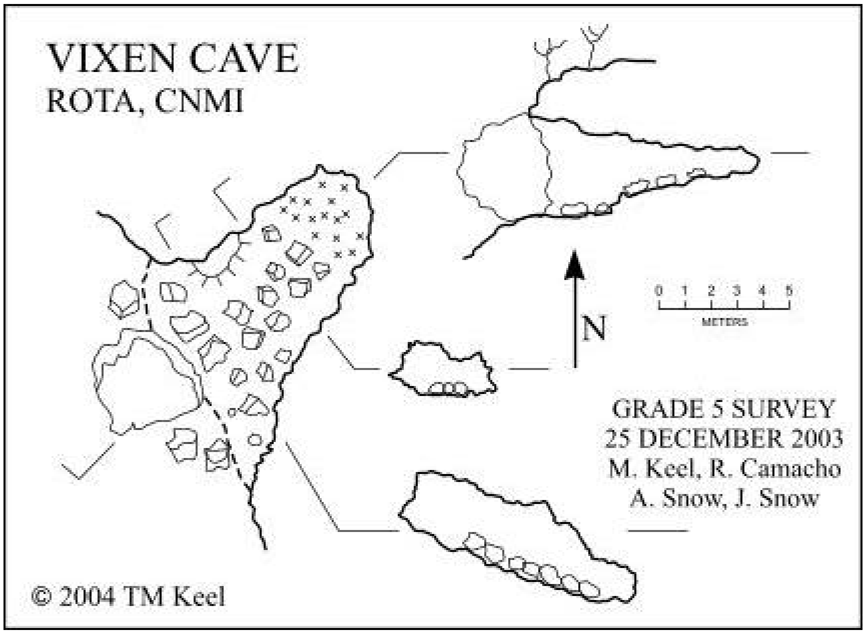

Figure 209: Map of Vixen Cave

Water Cave (Matan Hanum)

Water Cave, also known *As Matan Hanum*, Chamorro for "eye" and "water", is the primary source for municipal water for Rota. The cave is located in the *Talakhaya* area at about 350 m elevation at the contact of the volcanic rocks and the overlying limestone. The entrance to the cave is surrounded by a chain link fence. Inside the fence is an assortment of pipes and concrete tanks that are part of the water collection system. Some of the pipes collect water the issues from springs just outside the cave. The entrance to the cave has floor to ceiling chain link fence and a concrete dam. The main room of the cave is a roughly oval dome about 20m long (north-south) and about 18 m wide (east west). From the surface of the water, the ceiling is 5-6 m high. The east wall of the main room is mostly covered by flowstone over which cascades several thousand liters of water per minute. There is no accessible cave passage where the water erupts from the wall. At the north end of the room, a climb of about 3 m leads to a 7 m X 5 m X 2.5 m high room that also has much water coming into it from the east wall. The estimated height of the main chamber of Water Cave only includes the space above the water level. No attempt was made to measure the water depth. The water cave is thought to be a flank margin cave that happened to develop at the contact and later intercepted water flowing along the contact. The local geology leaves little doubt that this water comes from the *Sabana* on the top of Rota.

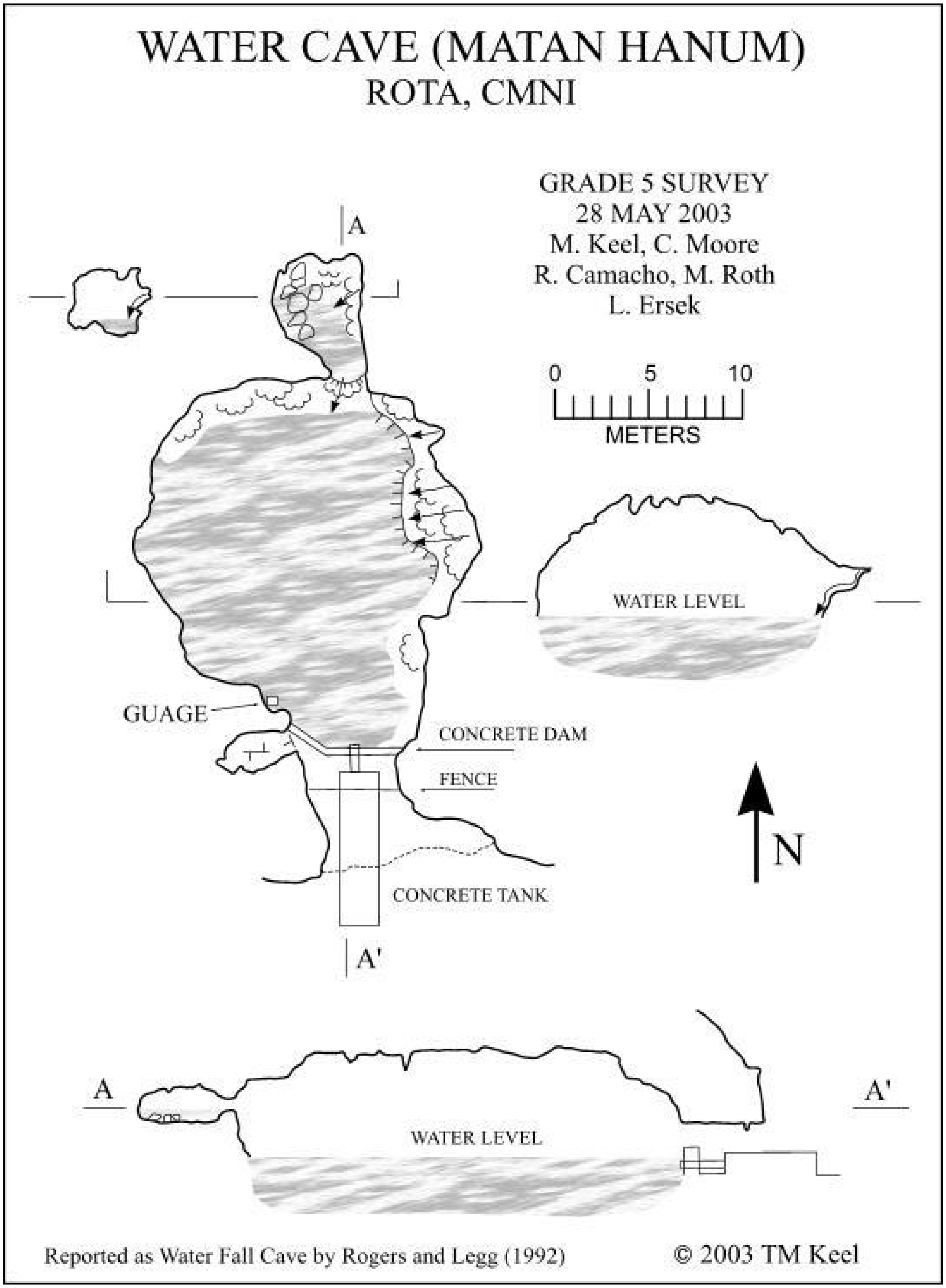

Figure 210: Map of Water Cave (Matan Hanum)

Mixing-zone Fracture Caves

Al-Su Cave

Al-Su Cave is located about 200 m east of *Taisacana* Museum Cave. *Al-Su* Cave is about 20 m long and is oriented roughly north south, with the entrance on the north end. The entrance is triangular and about 2.5 m high. The ceiling of *Al-Su* Cave quickly drops so that by 12 m into the cave the passage is less than 1 m high. At the rear of the crawlway is a small extension about 1 m long and wide.

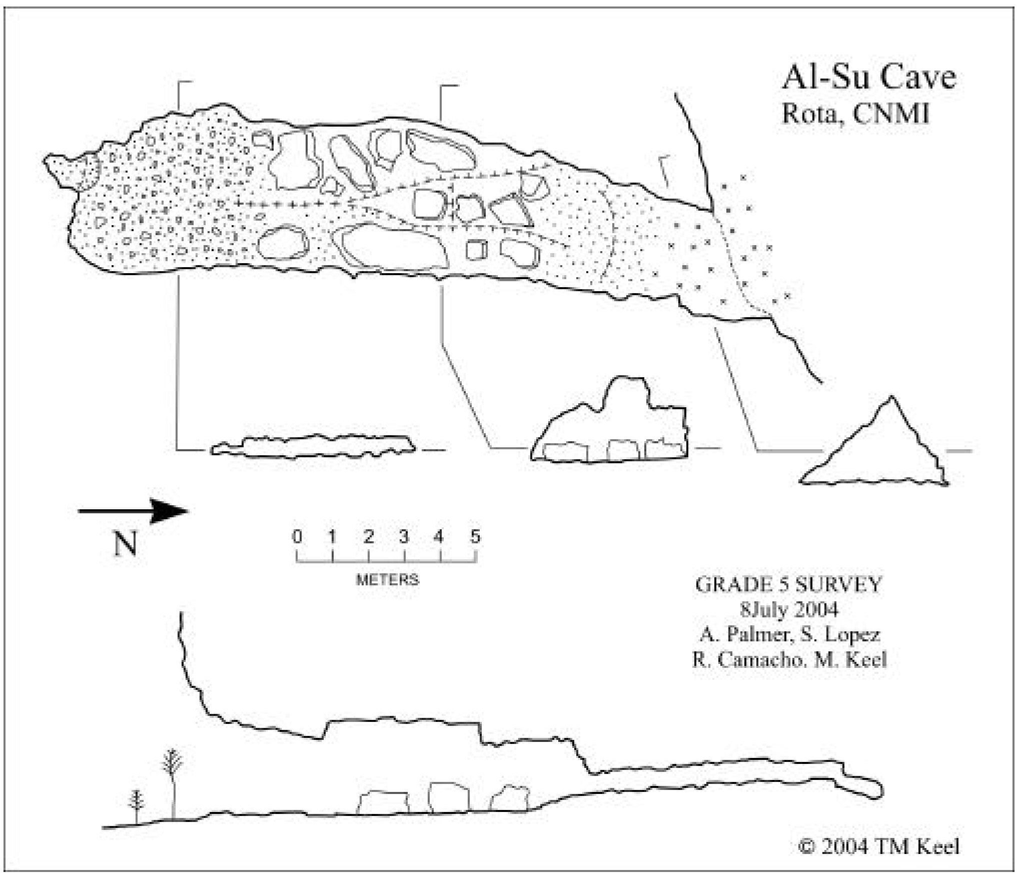

Figure 211: Map of Al-Su Cave

Canyon Cave

Canyon Cave is a small feature at the head of a canyon in the first terrace inland from the coast, south of *Alaguan* Bay, at about 15 m elevation. The cave and the canyon appear to be developed along a fracture (fault?) The cave extends about 9 m from the drip line and is about 14-15 m wide. The floor of the "C" shaped chamber is mostly covered with boulders and cobbles. It does not appear that the canyon adjacent to this small feature is the collapsed remains of a larger cave.

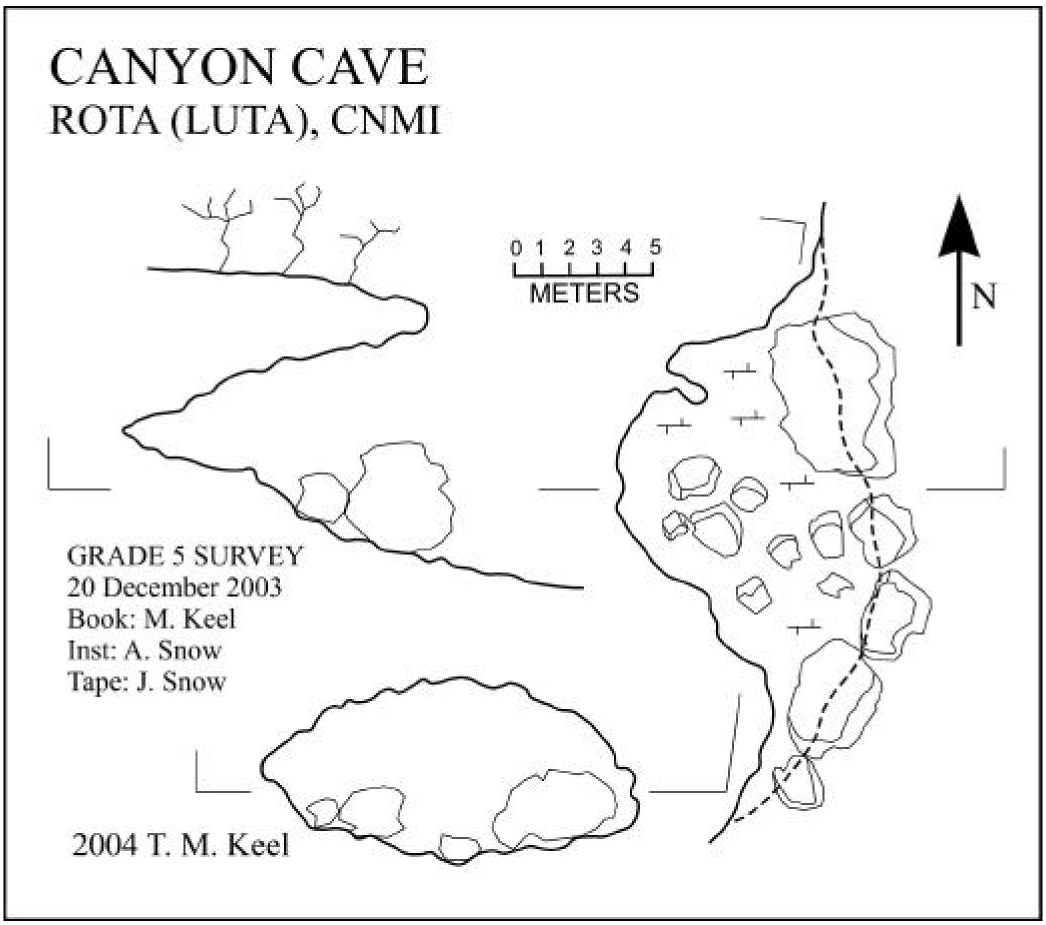

Figure 212: Map of Canyon Cave

Deer Cave

Deer Cave is the first large cave entrance south of the embayment at *Alaguan* Bay and is visible from the ocean. The entrance is about 20 m high and about 18 m wide. The ceiling grades down to about 10 m with about the same width for about 35 m, where the passage is nearly filled with a large breakdown block. Beyond this block, the cave narrows in height and width but continues for about 40 m before ending in an irregularly shaped room. The ceiling of the outer part of Deer Cave is highly decorated with phototropic stalactites.

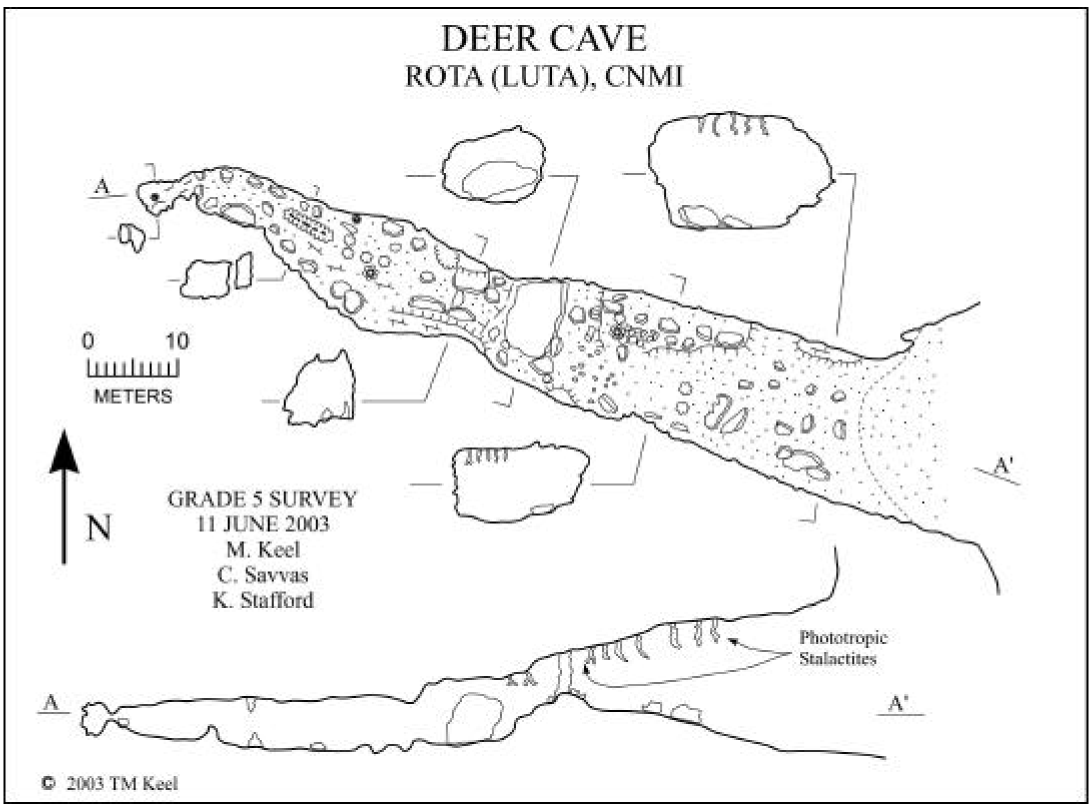

Figure 213: Map of Deer Cave

Four Crosses

In the cliff face southwest of *Ginalangan*, white crosses are visible in what appear, from a distance, to be cave entrances. A closer inspection reveals that there are actually four white crosses but no significant cave passage. About 20 m east of the crosses is an open sided chamber that may be a remnant flank margin cave. It is about 12 m wide, 7 m deep and 3 m high. The floor is built up level behind a man-made wall about 1 m high. There are steps through the wall leading up to the floor. About 20 m west of the crosses there is an open irregular chamber 10 m wide, 8 m deep and 8 m high. The crosses are located in an alcove that is developed along a fracture in the bedrock. The floor of the alcove has been highly modified by the construction of a manmade wall that has been filled in to create a narrow floor at the lower part of the alcove. The rest of the steeply sloping floor of the alcove is covered with a series of man-made steps. Slight overhangs on each side of the alcove converge at the fracture on which the alcove is developed.

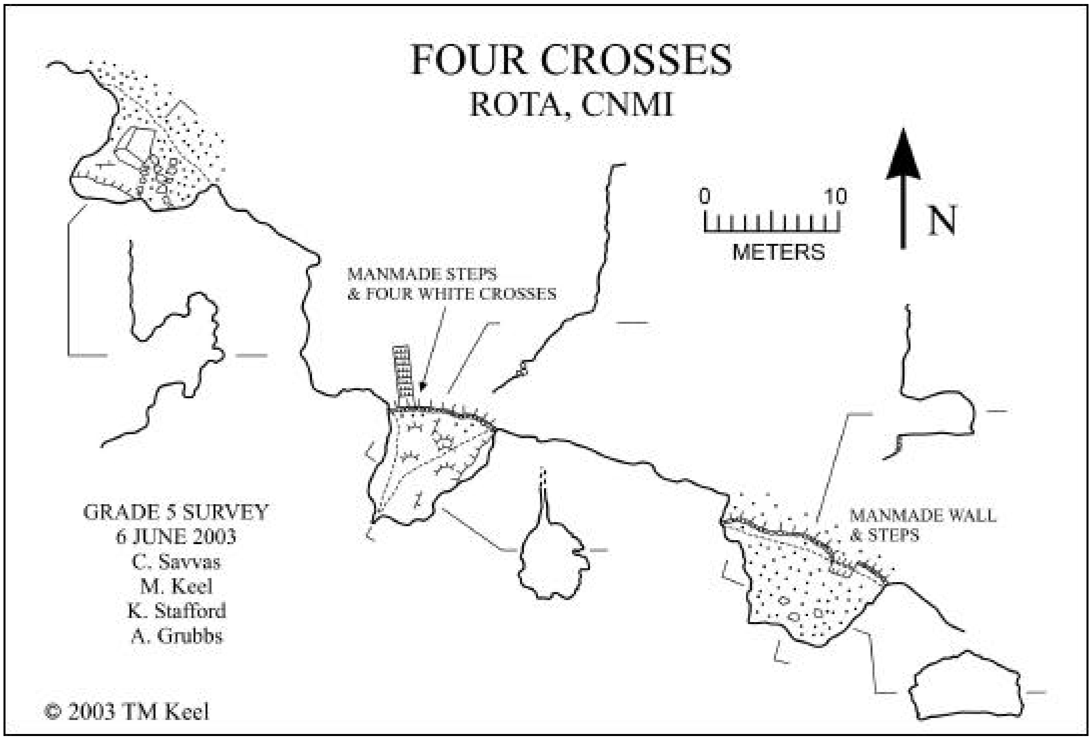

Figure 214: Map of Four Crosses

Hammer Cave

Hammer Cave is located in the cove west of *Sailigai Papa*, at about 60 m elevation. Hammer Cave is a linear cave developed along an obvious bedrock fracture. The entrance opens to the west and the cave is about 8 m long. The ceiling in the outer part of the cave is about 3.5 m high, but drops to less than 1 m about half way to the back. Hammer Cave is about 3 m wide at the entrance and gradually tapers toward the back. To the north of the entrance there is a small (< 1 m) passage that extends back parallel to the main cave for about 4 m.

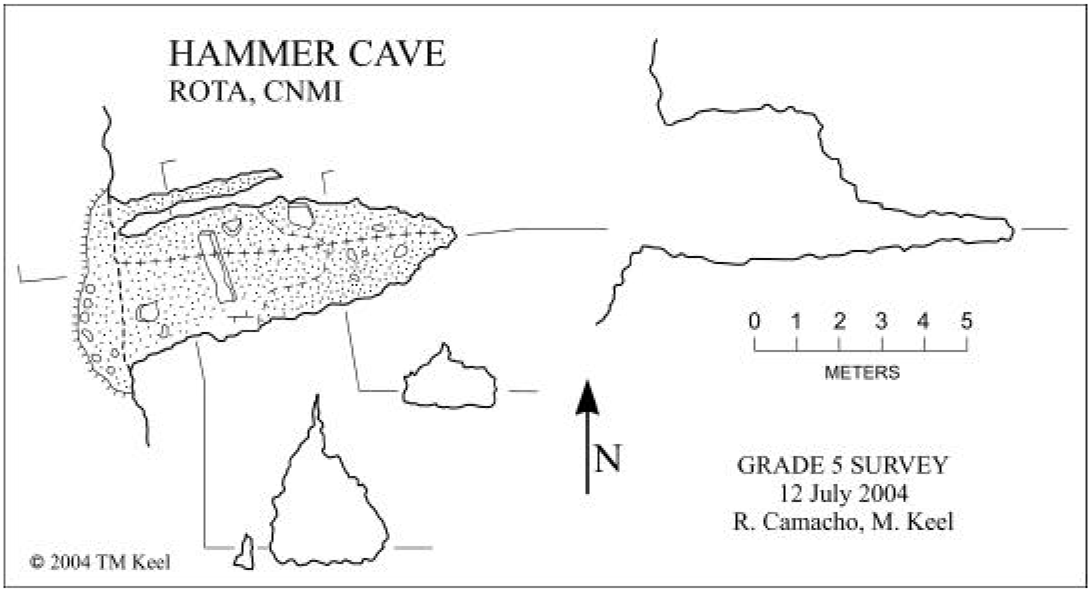

Figure 215: Map of Hammer Cave

Hang Out Cave

Hang Out Cave is located on the north coast of Rota, near *As Matmos*. Hang Out Cave is about 150 west of the much large feature called Surge Cave. Hang Out Cave is oriented northeast-south west and has entrances at both ends. The entrance on the northeast end is just above sea-level about 9 m from the entrance on the southwest. This pit-like vertical entrance is about 3 m deep. The cave is quite linear between the two entrances and is developed along an obvious fracture. The fracture forms a skylight along the length of most of the cave.

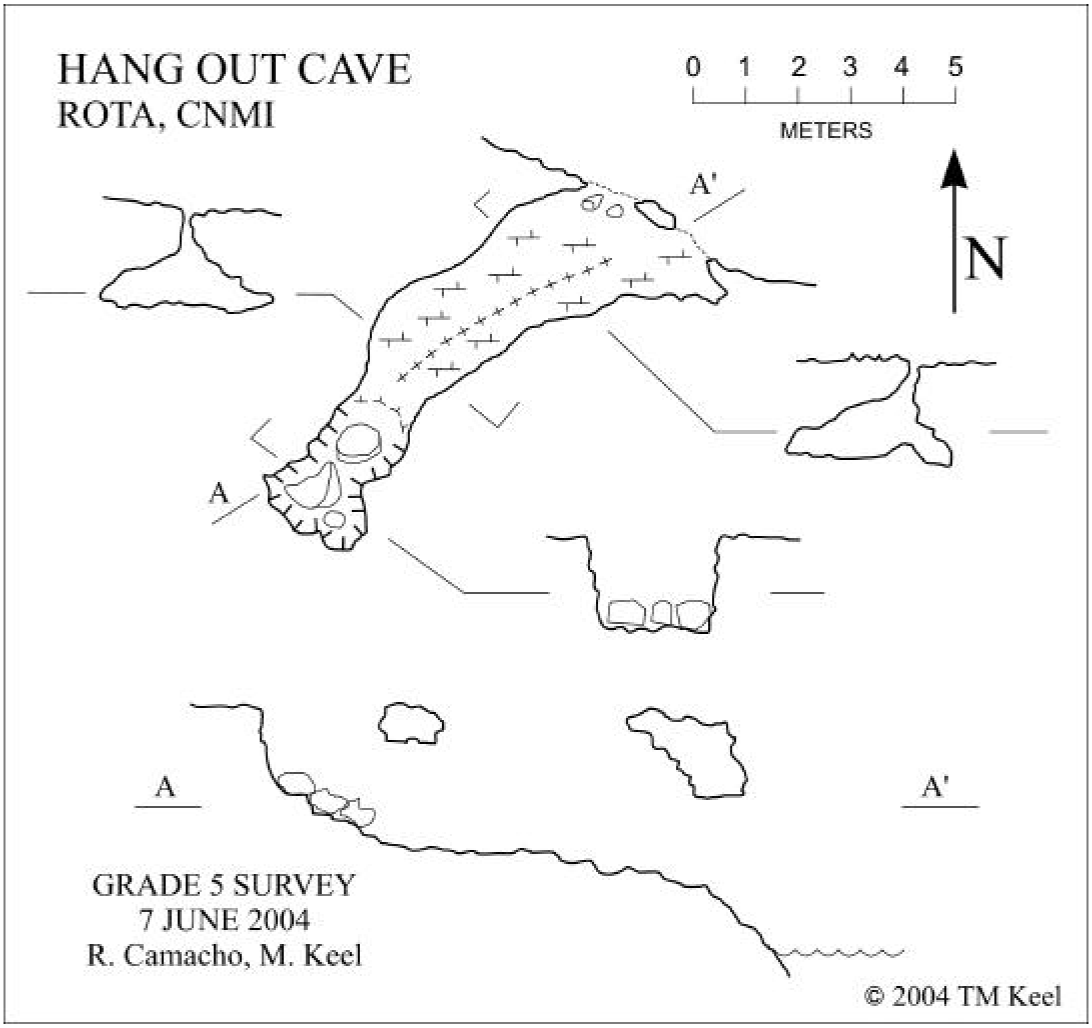

Figure 216: Map of Hang Out Cave

Incidental Cave

Incidental Cave is located near *Liyang* Perseverance at about 80 m elevation directly west of *Puntan Haina*. The entrance is about 20 m wide and about 10 m high. The ceiling slopes steeply down as the floor also comes up, such that at about 7 m back from the drip line the cave is about 4 m high. The ceiling and the floor continue rising at about the same slope before the cave ends at about 20 m. The floor of the cave is entirely recemented rubble, giving the impression that the entrance to the cave was filled from the inside. The area above the cave should be investigated for a possible collapse feature.

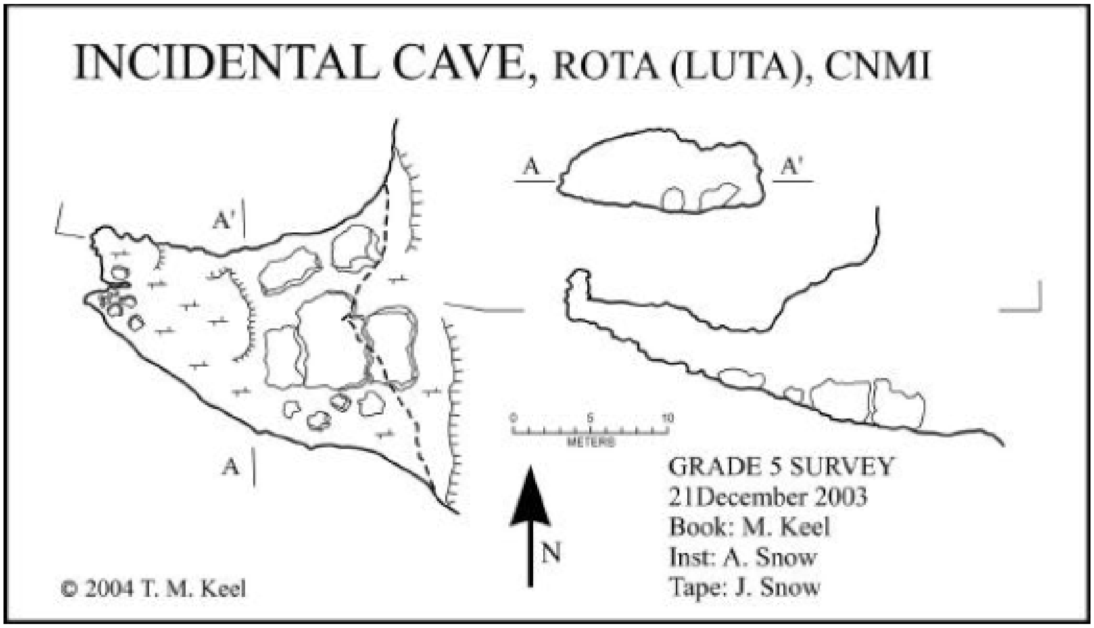

Figure 217: Map of Incidental Cave

Liyang Alapin

Liyang Alapin is located on private property at the base of the cliff directly north of the road to *Poña Point* overlook. The cave is developed sub-parallel to the cliff face and appears to be developed along the prominent fracture that strikes at 213°. The entrance to the main part of the cave is 5 m high by about 7 m wide. The drip line extends on both sides of this entrance, incorporating a high, shallow overhang to the south, which shows manmade modification, and incorporating a smaller overhang to the north with the remains of a large stalagmite, indicating that the entire outer portion of the cave was once enclosed. The ceiling of the main room, just inside the entrance, slopes from southeast to northwest and is clearly developed along a bedding plane. The 7 m high vertical wall on the southeast is developed along a (bank-margin?) fracture. The crack extends an undetermined distance into the cave ceiling. About 25 m into the cave, the passage developed along the prominent fracture narrows to 3-4 m wide variably and ends after 10 m more. To the right, at the entrance to this narrower section, a passage 4-8 m wide extends for about 15 m. About 15 m inside the main entrance there is an overhang low on the left wall. Under this overhang there is a short dead end passage to the left. To the right leads down a short slope to a room about 4 m across and about 1.5 m high. A low crawlway leading northwest from this room leads to a room about 1.5 m across and about 1m high. An impassable hole leads northwest from this room and admits some daylight.

Exploration on the surface revealed an entrance to a 15 m passage that that connects to this small hole. This section the cave is parallel to the main cave.

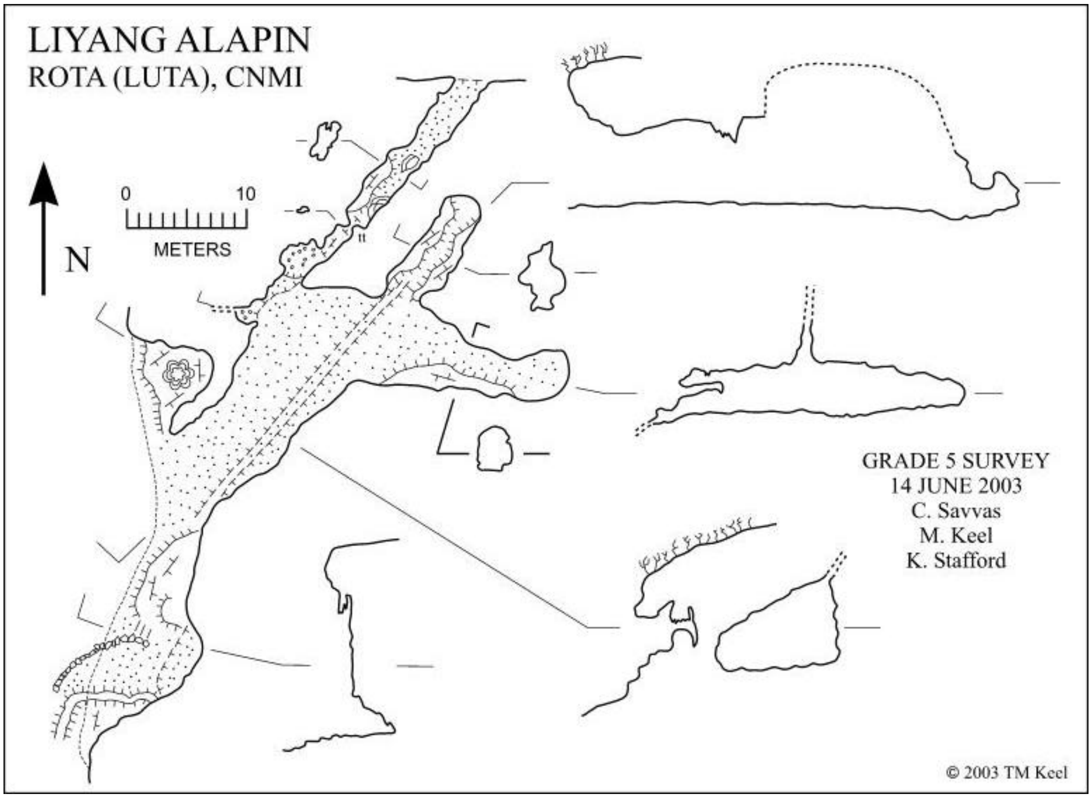

Figure 218: Map of Liyang Alapin

Liyang Ganas and Nanong Kastiyu

Adjacent to *Songsong* Village, about 70 m ESE of *Tonga* Cave, are *Liyang Ganas* and Nanong *Kastiyu* (Rogers and Legge, 1992), which are two caves connected with a manmade tunnel. The tunnel is located about 5 m inside *Liyang Ganas*. Both caves have terraces held in place by stone walls. Compared the somewhat globular morphology of *Liyang Tonga*, these two caves are much more linear. The smaller, western-most *Nanong Kastiyu* is about 18 m long and 4 m wide, oriented NE/SW. The entrance to the larger cave, *Liyang Ganas*, is about 15 m east of the smaller cave. It runs along the same trend, but is about 58 m long and 7 to 18 m wide. About 2/3 of the way back into the larger cave the distance between the walls widens to form a room just north of the main trend of the cave. Both caves are apparently developed along the fractures that are visible in the ceiling of each cave. The drip line of the larger cave is incised along the fracture.

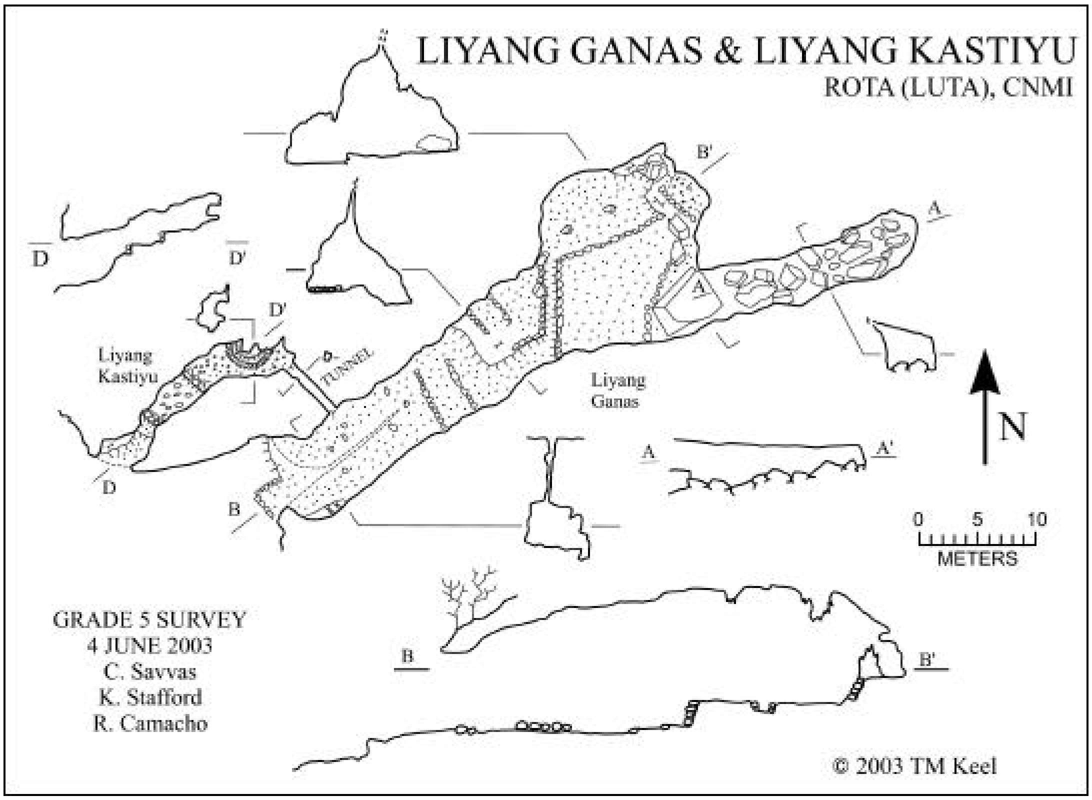

Figure 219: Map of Liyang Ganas and Liyang Kastiyu

Liyang Perseverance

Liyang Perseverance is the largest of the cave entrances visible from *Puntan Haina*, just below the cliff top at about 80 m elevation. Perseverance is about 23 m wide at the entrance and narrows to about 12 m for most of its length. It ends about 20 m back from the drip line. The ceiling of the cave is roughly level but there is dramatic relief in the floor in the entrance area, giving the entrance an uneven key hole profile when seen from a distance. The ledge that makes up this higher floor in the south side of the entrance has several large, weathered, algae-covered speleothems. Overall, the floor of the cave rises irregularly to the rear. A large part of the ceiling has collapsed creating a skylight 5+ m across. About 2 m west of the large skylight there is another much smaller skylight that can be reach by free climbing. Perseverance shows some evidence of having developed along a fracture, but erosion has altered the cave such that fracture control is difficult to confirm. Much of the outer part of the cave has apparently been destroyed by cliff retreat.

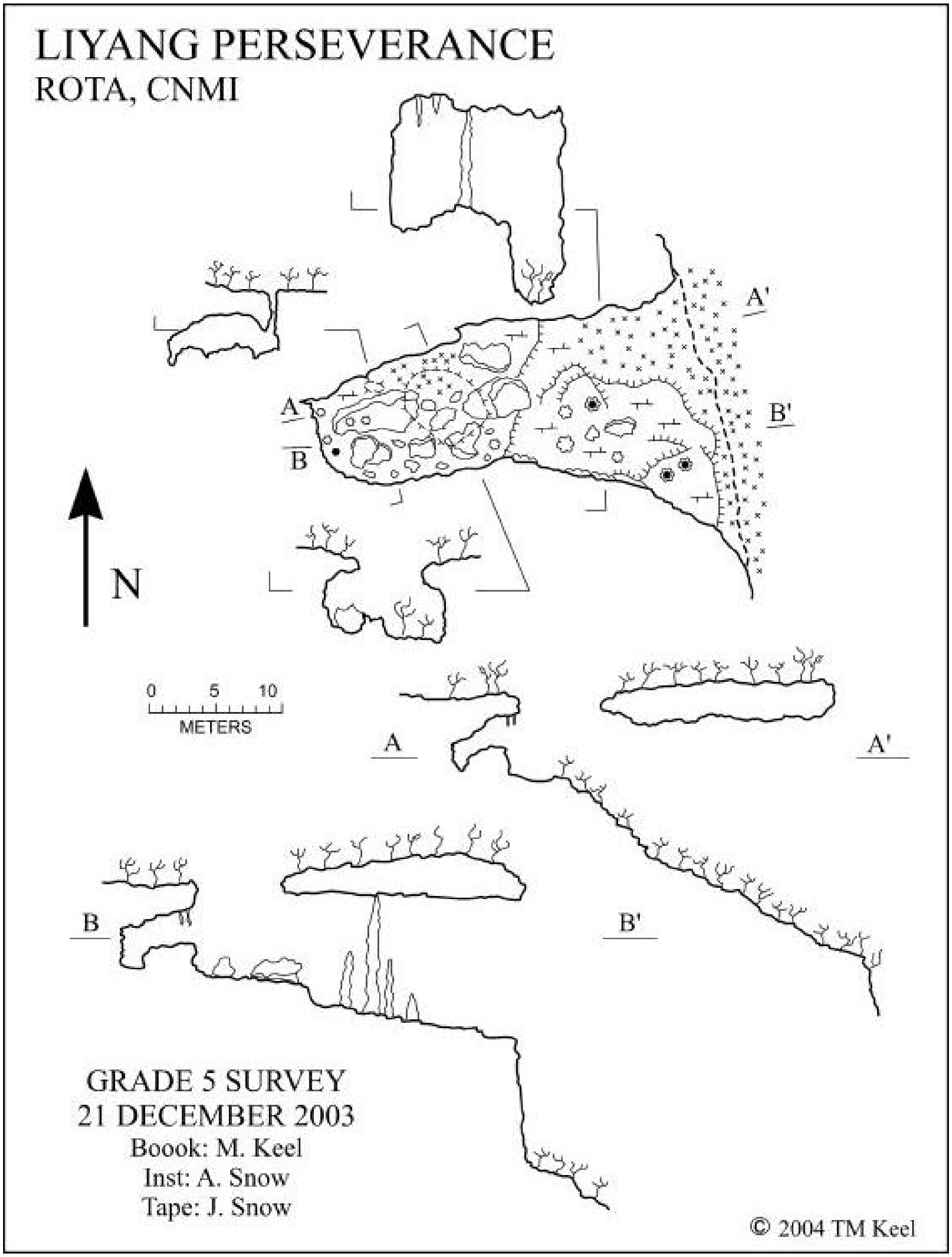

Figure 220: Map of Liyang Perseverance

Liyang Tonga (Taga)

Tonga Cave, a large remnant of an apparent flank margin cave, is prominent land mark in *Songsong* Village. It is about 65 m long and about 30 m wide, oriented north-south. *Tonga* Cave has an entrance, about 25 m wide by 8 m high, on the west side of the upper large chamber and a second, more commonly used entrance (3 m wide, 5 m high) off the southwest corner of the large chamber. To the south of the smaller entrance is a lower, much smaller chamber that is completely open on one side. It was mapped as part of *Tonga* Cave because it is contained within the same drip line. *Tonga* Cave contains significant human modifications including concrete and stone steps, concrete slabs, a small shrine, and even a barbeque grill. The cave has reportedly been used as a shelter during typhoons. The floor and ceiling are decorated with speleothems, including phototropic stalactites. Immediately east of the smaller entrance to *Tonga* Cave a shrine and several tunnel entrances. The tunnels were investigated sufficiently to determine that they are not natural features but they were not mapped.

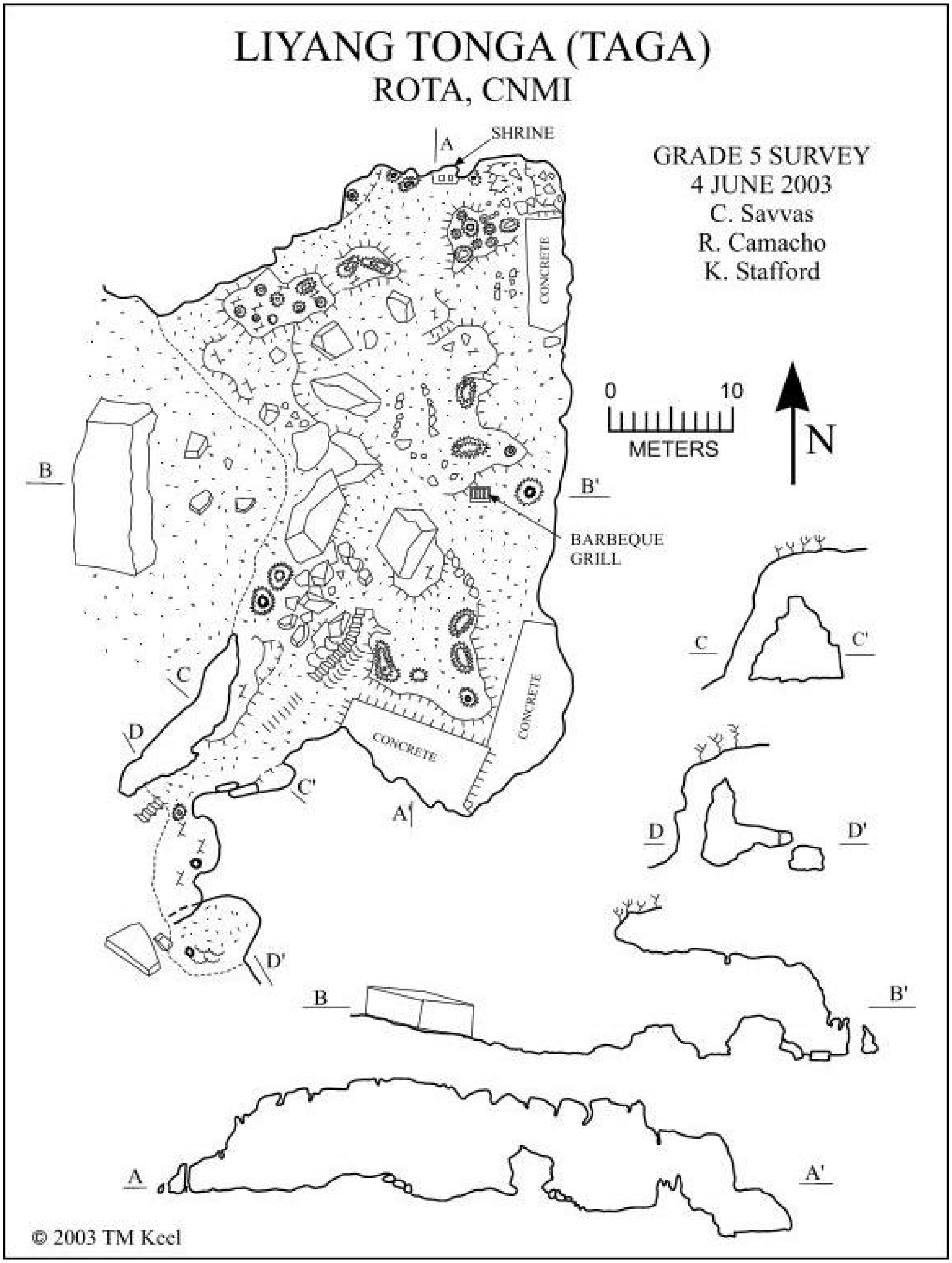

Figure 221: Map of Liyang Tonga (Taga)

Rainy Day Cave

Rainy Day Cave, located in the south wall of the cove west of *Sailigai Papa*, is reached by a 4 m climb. The cave is about 15 m long and 2-3 m wide before tapering into a fracture at the rear. The Rainy Day Cave is developed along a fracture that is expressed along the full length of the ceiling of the cave. The ceiling ranges from 2.5 to 7 m high. The floor slopes steeply up at the rear.

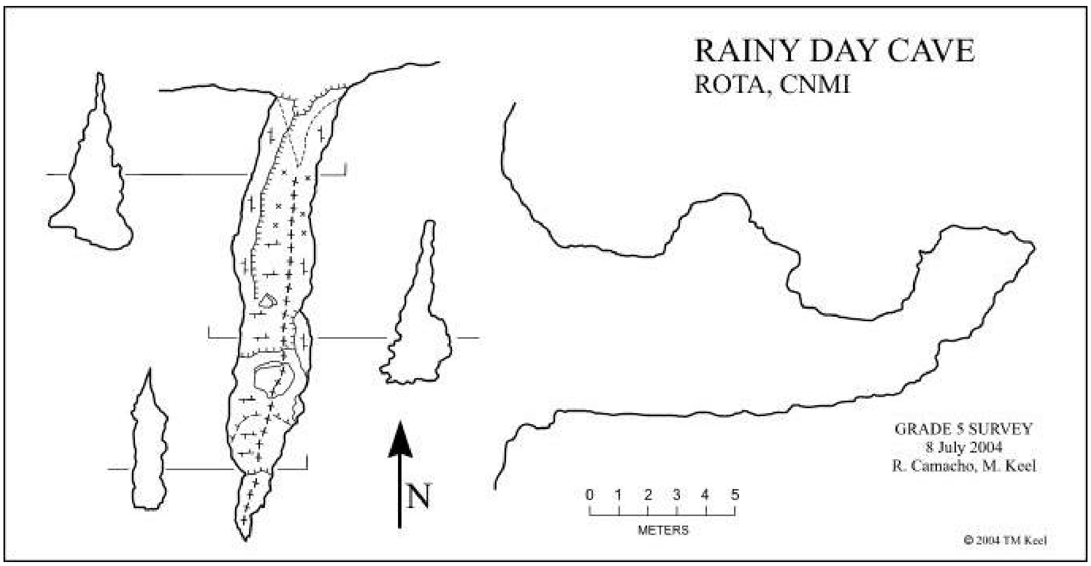

Figure 222: Map of Rainy Day Cave

Rock Pile Cave

Rock Pile Cave is located in the cove west of *Sailigai Papa*. The 4 m wide by 5 m tall entrance is reached by a 3 m climb. Rock Pile Cave faces north and extends for about 10 m from the drip line. The floor on the east side of the cave is bare limestone with a few cobbles. On the west side of the cave, the floor drops away into a solutionally widened fissure that extends down about 5 m below the main floor of the cave. Rock Pile Cave is developed along the same fracture as this floor fissure.

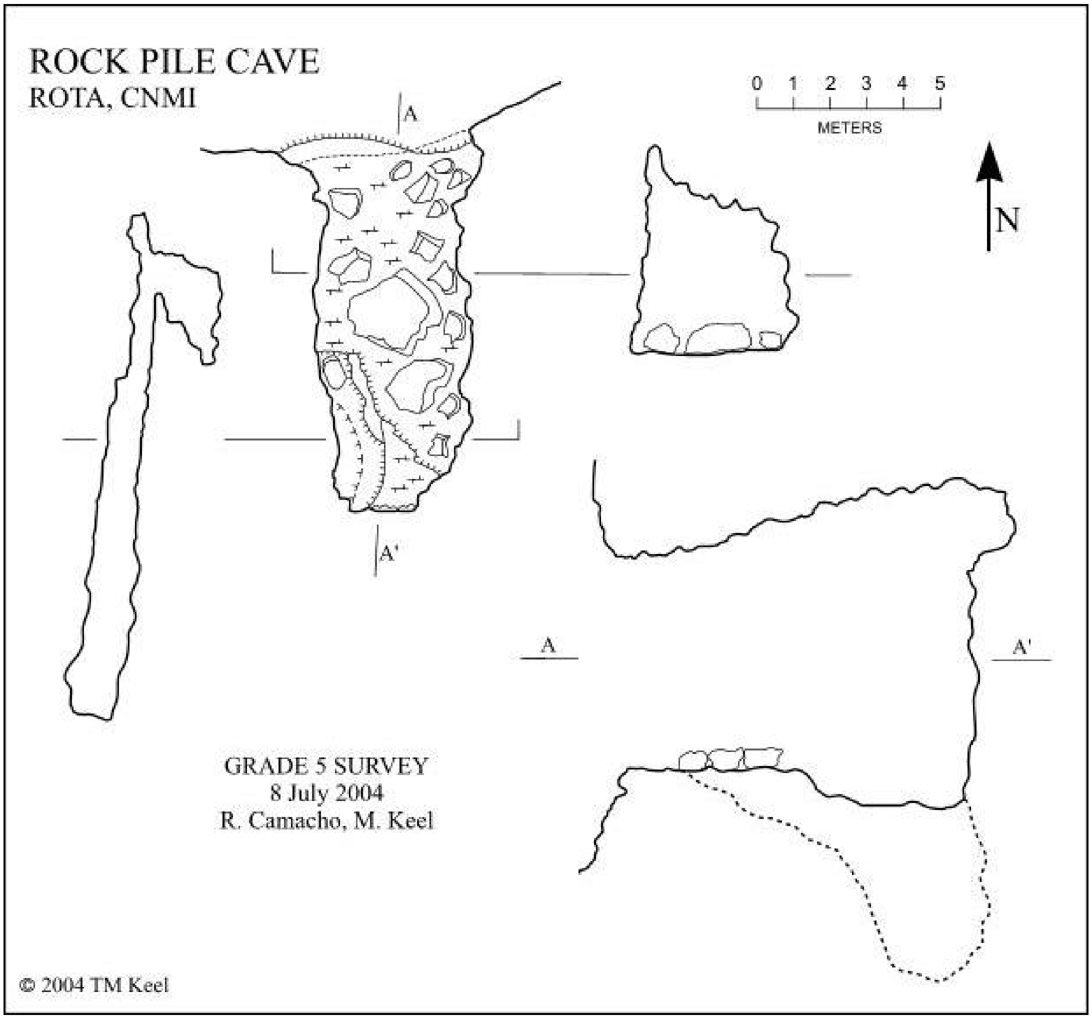

Figure 223: Map of Rock Pile Cave

Second Chance Cave

Second Chance Cave is the second largest of the cave entrances visible from *Puntan Haina*, just below the cliff top at about 80 m elevation. Second Chance Cave is located a few meters south of the larger *Liyang* Perseverance. Second Chance Cave in nearly inaccessible from below, due to the steep cliff face, but is easily accessible through a skylight entrance along the south wall near the west end of the cave. There is another, barely passable skylight entrance about 4 m back from the drip line. There are several other places where light shines through the very thin ceiling of Second Chance Cave. From inside the cave, the ceiling has the appearance of being composed of cemented cobbles and boulders. This facies is not evident in the walls of the cave. The cave extends about 30 m back from the drip line and is variably 7 m wide, tapering toward the rear. The cave is about 7 m high at the entrance and tapers gradually to the rear where there is a significant ceiling drop. The floor is primarily bed rock with some soil cover and some cobbles and boulders. Second Chance Cave is apparently developed along a fracture. The facies in the cave ceiling suggests that possibly the cave developed in a wide fracture that was filled with cemented rubble or cemented breakdown.

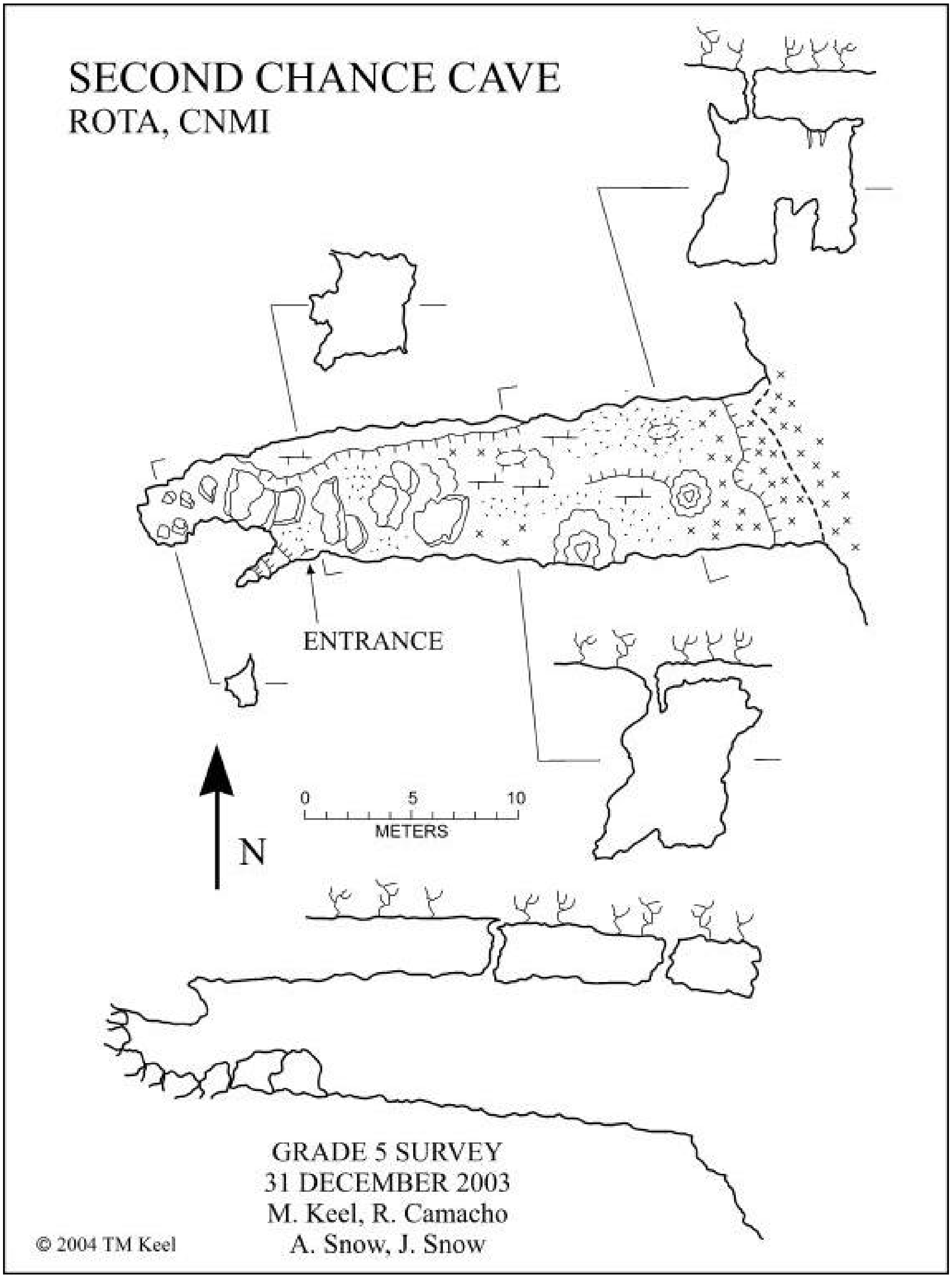

Figure 224: Map of Second Chance Cave

Taisacana Museum (Antigo) Cave

Taisacana (*Antigo*) Museum Cave is located beside the main highway, about 1.5 km northeast of *Songsong* Village, at *Esong*. The entrance to the cave is covered by doors under a building that is built above the entrance. The first 30 m of the cave consists of a linear room variably 5 m wide and starting at 2.5 m high rising to about 10 m. Beyond 30 m the cave widens into a room 25 m by 18 m by about 12 m high, with the long axis orientated the same way as the entrance passage. At the back of the larger room, a short climb-up leads to a tall narrow room that pinches down to an impassable crack. The floor of the most of the cave is packed soil. The trend of the entire cave is along a fracture that strikes at 154°. The fracture along which the cave is developed is prominent in the ceiling for most of the length of the cave. The cave is a privately owned museum and houses an extensive collection of artifacts from the Chamorro, Spanish, German, Japanese, and American eras of Mariana Islands history.

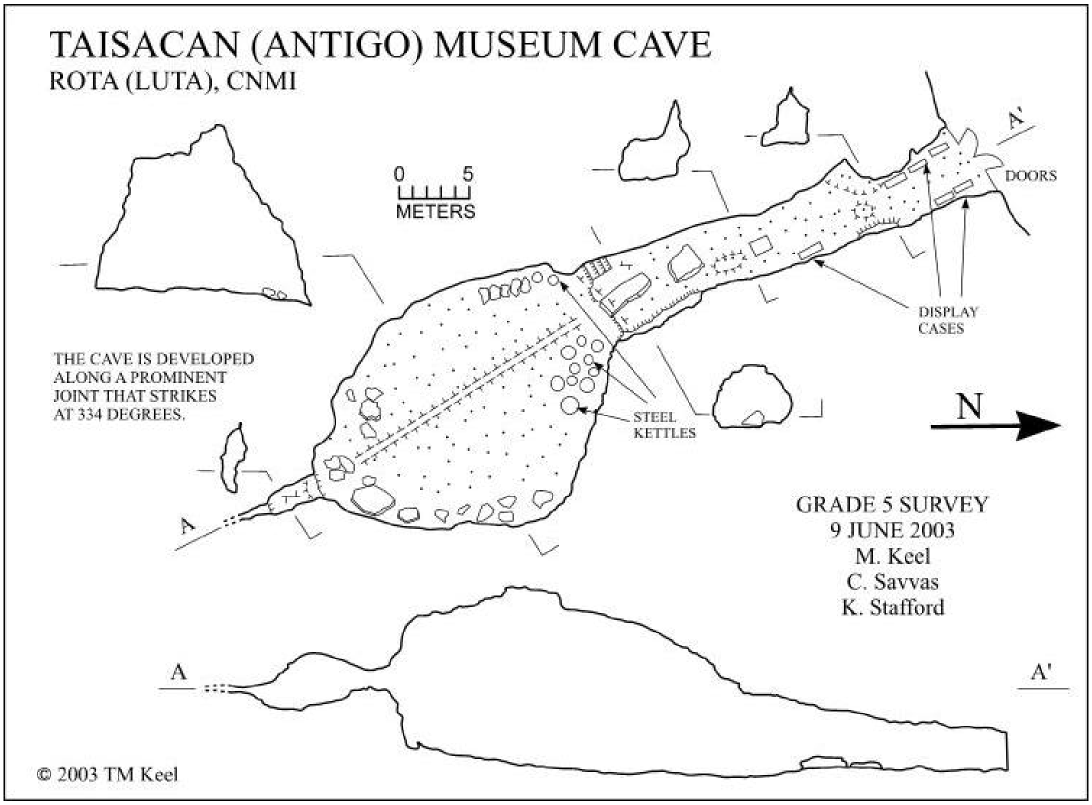

Figure 225: Map of Taisacana (Antigo) Museum Cave

Sea Caves

Alaguan Sea Cave A1

This small feature was mapped as an example of a sea cave, the development of which appeared to be almost entirely controlled by physical erosion as opposed to dissolution. It is located at about 10 m elevation near *Alaguan* Bay at the base of the large embayment that dominates this section of coast. It consists of about 11 m of drip line and only extends back about 5 m.

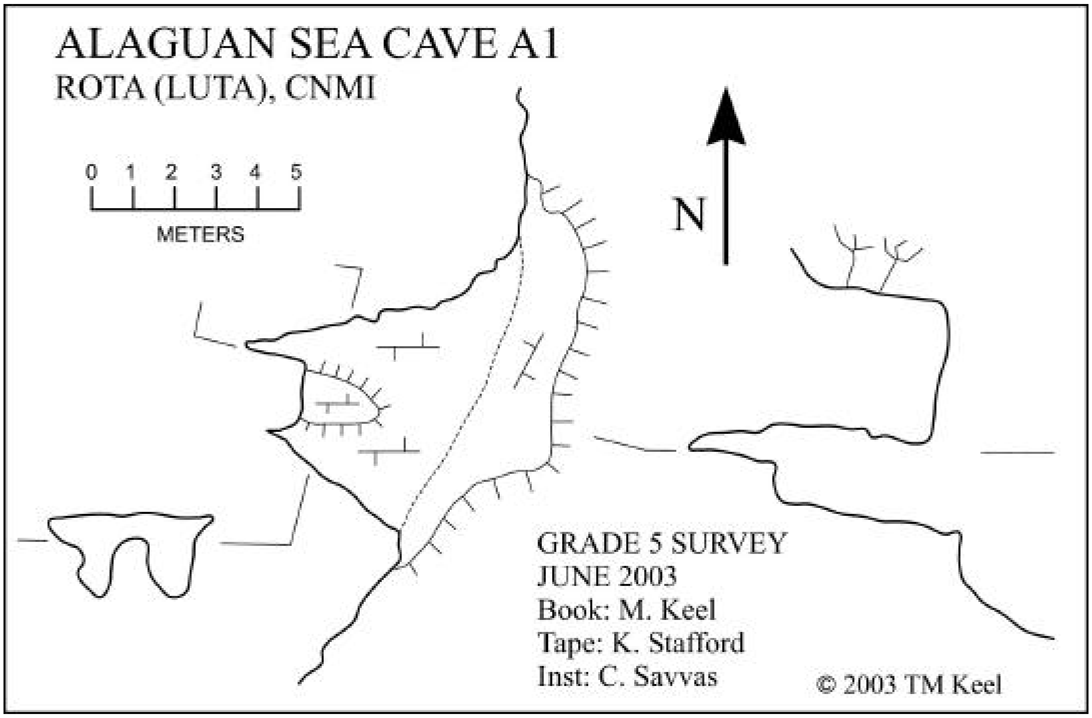

Figure 226: Map of Alaguan Sea Cave A1

Double Cave

Double Cave is located about 2 m above sea level, at the base of the cliff, near the western end of the rocky beach between *Puntan Malilok* and *Gaonon*. Double Cave consists of two large main chambers and was formed in fore-reef beds. The two large chambers are connected near the rear by a passage less than 1 m in maximum dimension. The westernmost chamber is about 20 m wide and extends about 12 m back from the drip line. The easternmost chamber is also about 20 m wide and extends about 20 m back from the drip line. Both chambers are completely open to the outside and floored with boulders, cobbles, beach sand, and storm tossed debris. A low, narrow section of the cave extends from the east end of the eastern-most large chamber. Double

Cave is either a flank margin cave heavily overprinted by wave driven erosion or is simply a sea cave formed primarily by erosion.

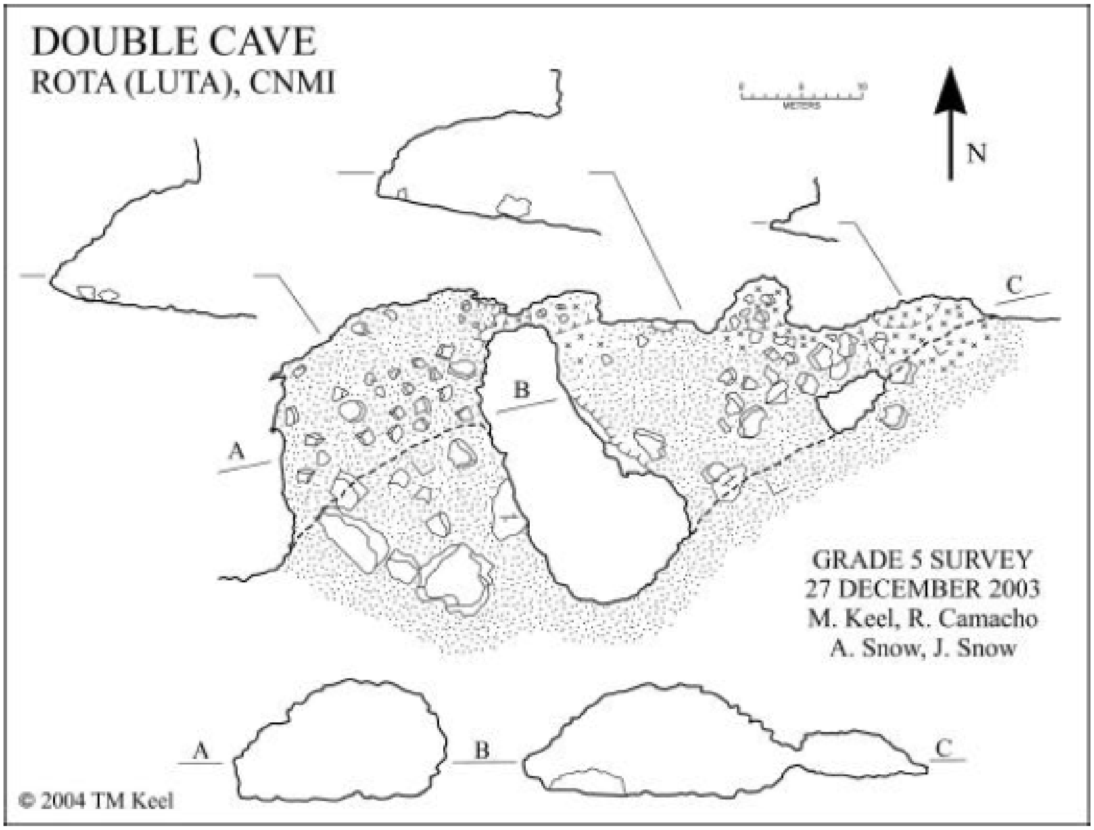

Figure 227: Map of Double Cave

Poña North Sea Cave

Poña North Sea Cave is located at about 3 m elevation, at the bend in the cliff face on the north side of *Poña Point*. The cave shows very strong expression of fore-reef beds. The *Poña* North Sea Cave is about 25 m wide at the drip line and extends back about 15 m, narrowing quickly toward the back. The floor dips steeply to the south along the fore reef beds. The irregular overall shape of this cave strongly suggests that physical wave erosion has been the main factor in its formation.

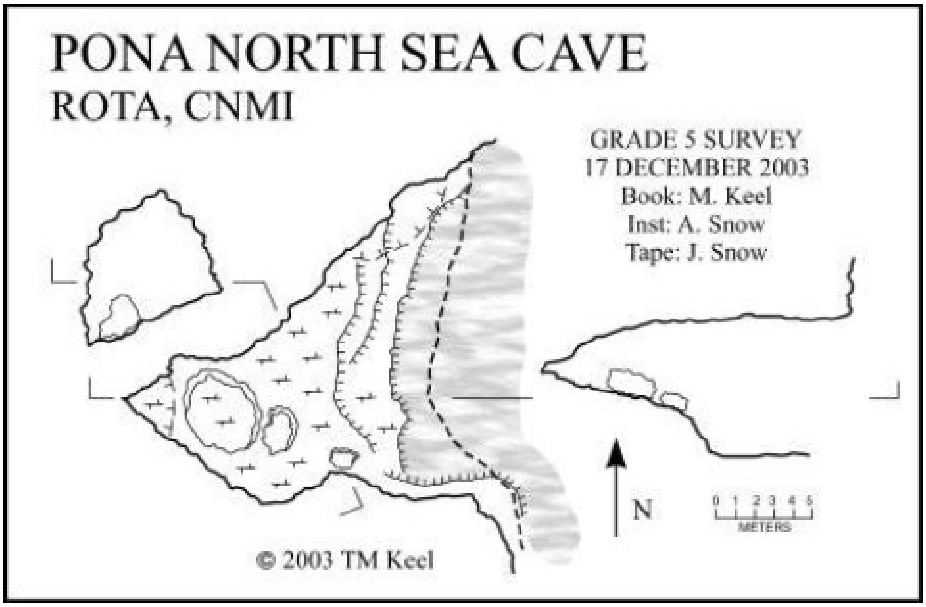

Figure 228: Map of Poña North Sea Cave

Cave of Unknown Origin

Mendiola Cave

Mendiola Cave is located at about 160 m elevation, above the second right hand switch back on the road leading up the Water Cave. The cave consists primarily of a large oval chamber about 30 m across. The floor of the chamber slopes irregularly downward and is covered with sand, cobbles and boulders plus some vegetation. There are two small rooms off to the left of the entrance and a deposit of reddish brown clay at the bottom of the wall on the left rear. On the right rear is a small (0.25 m) pool of water where the cave barely intersects a stream with flow on the order of 10 liters per minute in May 2003. This area does not show evidence of flooding but is probably very close to the volcanic basement rock.

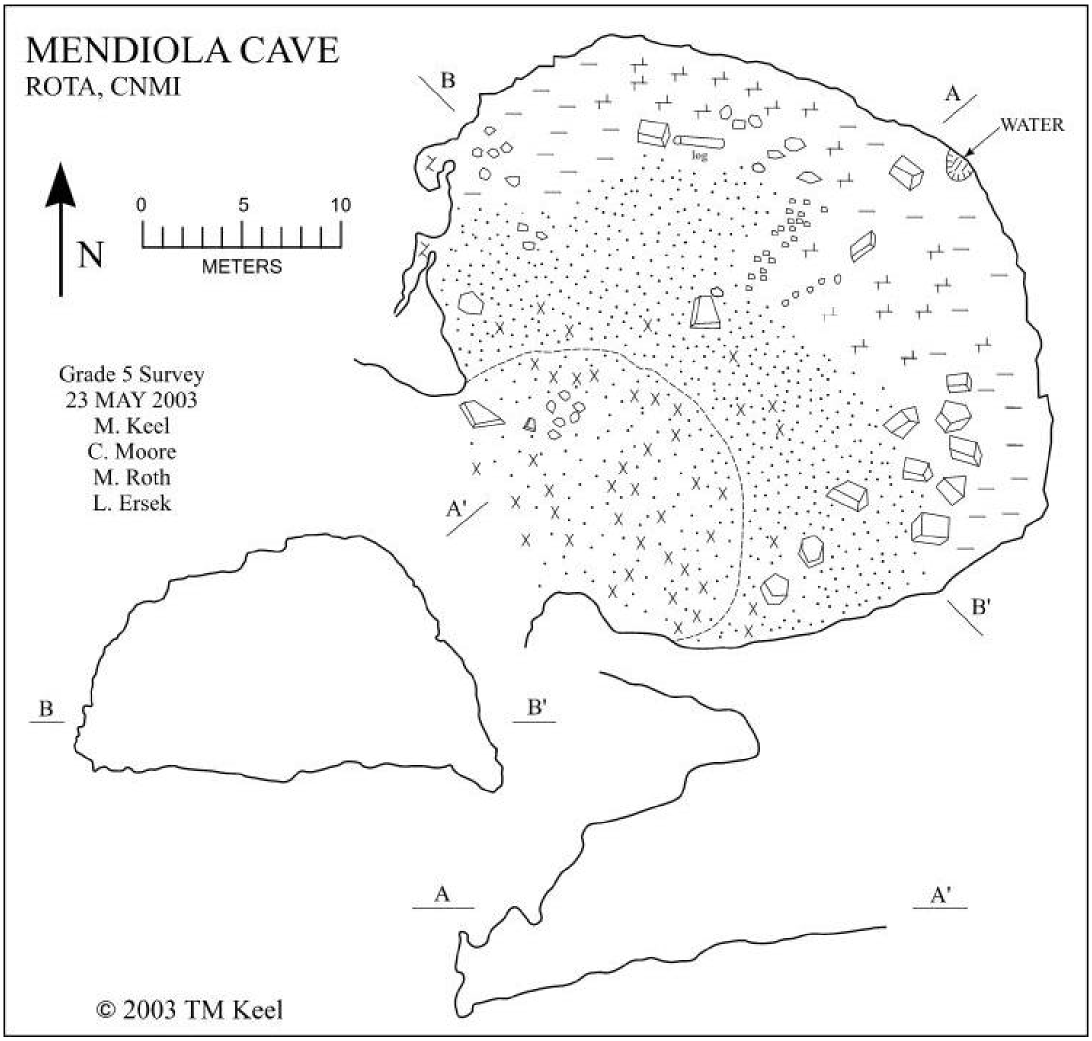

Figure 229: Map of Mendiola Cave

Man-Made Features

Kaigun 223 Japanese Command Post

Although this site contains no real caves, *Kaigun* 223 Japanese Command Post is documented here as an example of the World War II era tunnels that are common on Rota. It is located in the northeast facing cliff at *Ginalangan* at about 240 m elevation, south of the white crosses prominently visible in the same cliff face (Four Crosses). This site has extensive human modification including at least four pill boxes, three cisterns, a defensive wall running about 160 m, and several man-made tunnels most of which have barrier walls at their openings.

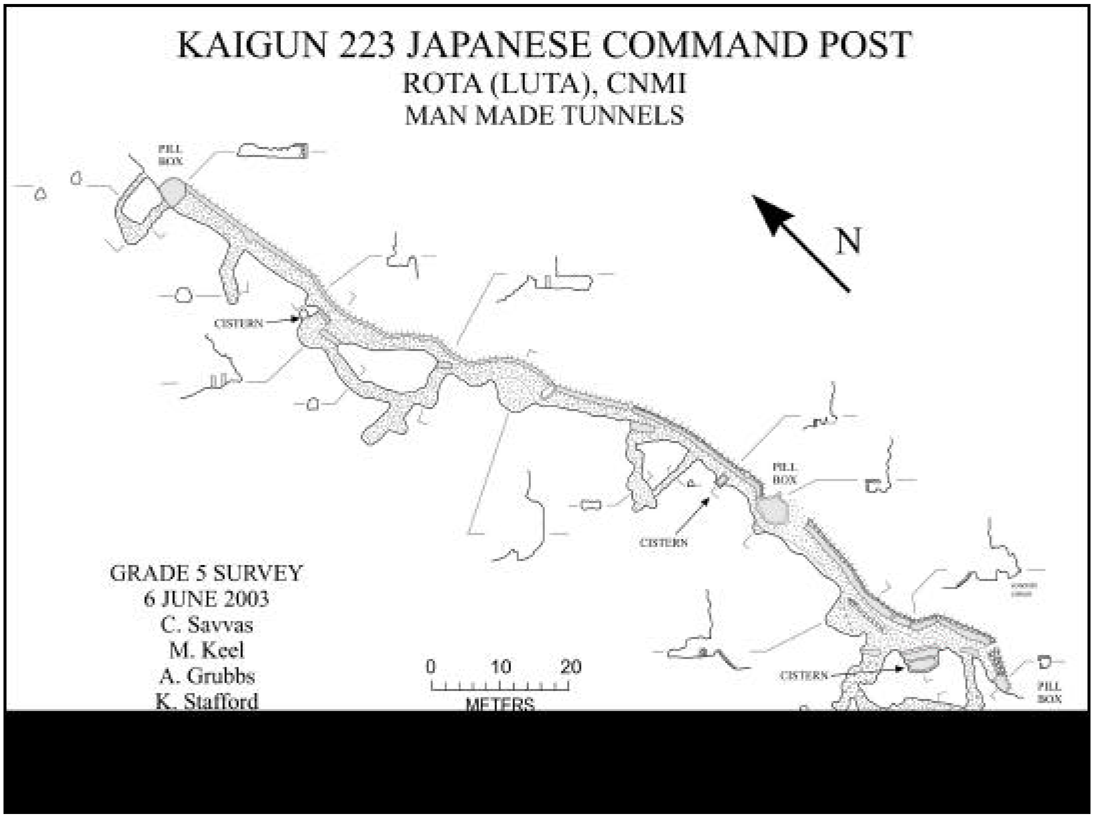

Figure 230: Map of Kaigun 223 Japanese Command Post

Peace Memorial Tunnels

Located under the volcanic boulders just north of the *Sabana* Peace Memorial, this feature is clearly a set of manmade tunnels and were surveyed as an example of such.

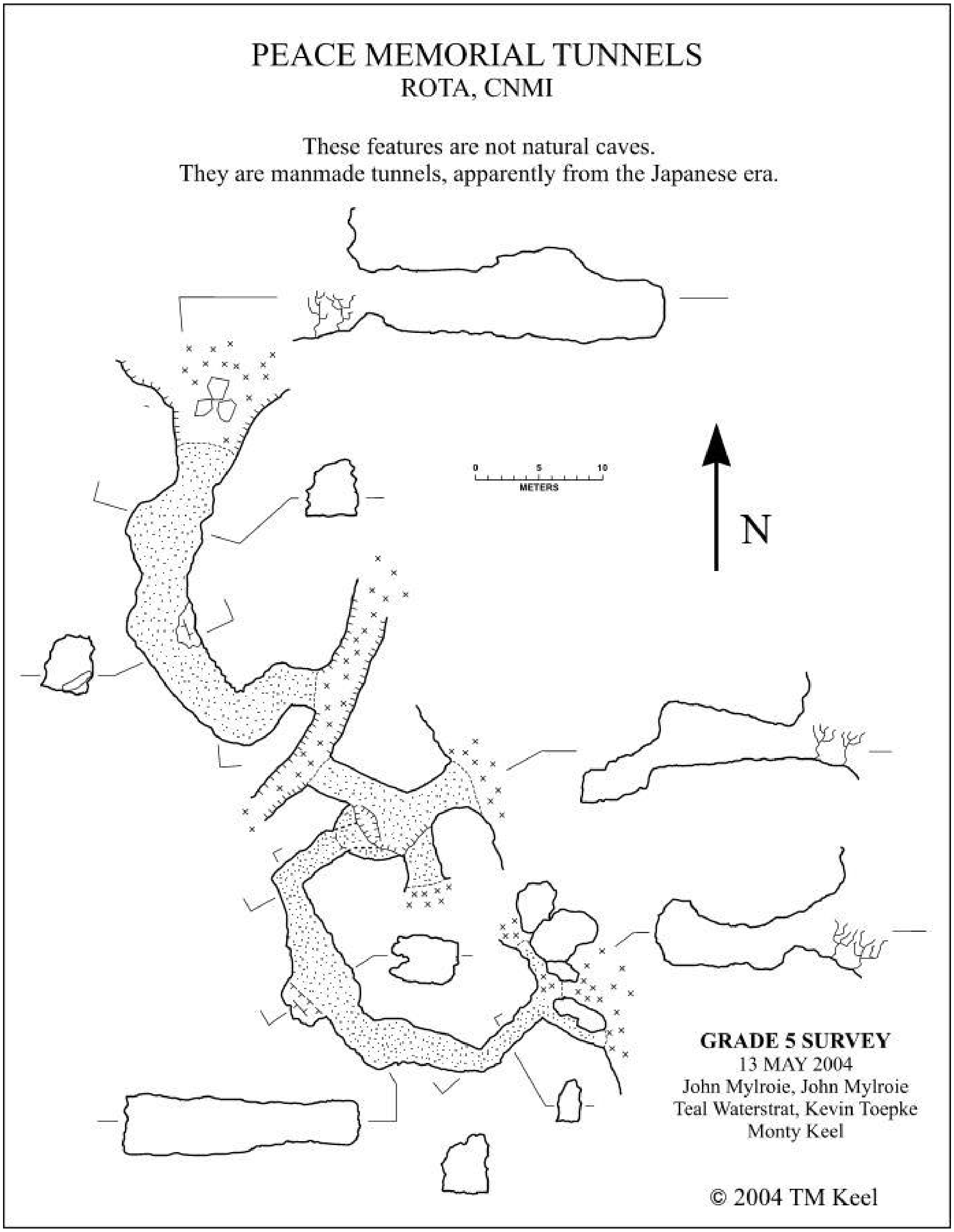

Figure 231: Map of Peace Memorial Tunnels

Flank Margin Caves

Bare Foot Cave

Barefoot Cave is located at sea-level in the *Chenchon* Bird Sanctuary, below a large reddish patch of rock in the inland cliff. Barefoot Cave has two entrances, both of which contain sea-level pools. The two entrance areas are connected via multiple, small sea level passages, only one of which was found to be passable below the surface. The southwest section of Barefoot Cave extends about 22 m inland while the northeast section extends about 17 m. The morphology of Barefoot cave suggests that it is a sea cave developed primarily by physical erosion with some possible contribution by mixing dissolution.

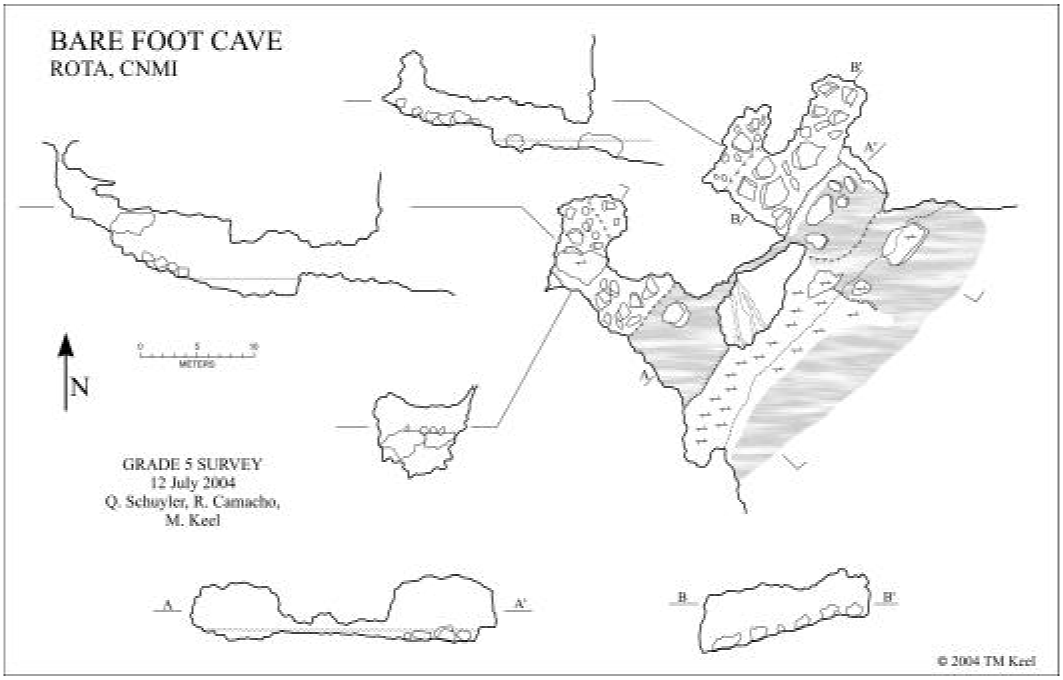

Figure 232: Map of Bare Foot Cave

Buffalo Cave

Buffalo Cave is a section of the flank margin cave horizon at *As Matmos*. Buffalo Cave consists of two levels, both of which are completely open on the north side. The lower level opens at the same elevation as the adjacent coastal bench, extends about 30 m east west and a maximum of about 6 m into the cliff face. The east end of the lower section is 1-2 m high and includes a bedrock pillar. The west end of the lower section is more enclosed and contains a manmade wall of loose laid limestone cobbles and boulders, below a point where the ceiling reaches about 3 m. The upper section of Buffalo Cave extends back from the drip line a maximum of about 12 m and is about 40 m long east west. The upper section contains numerous phototropic speleothems, and extensive flowstone.

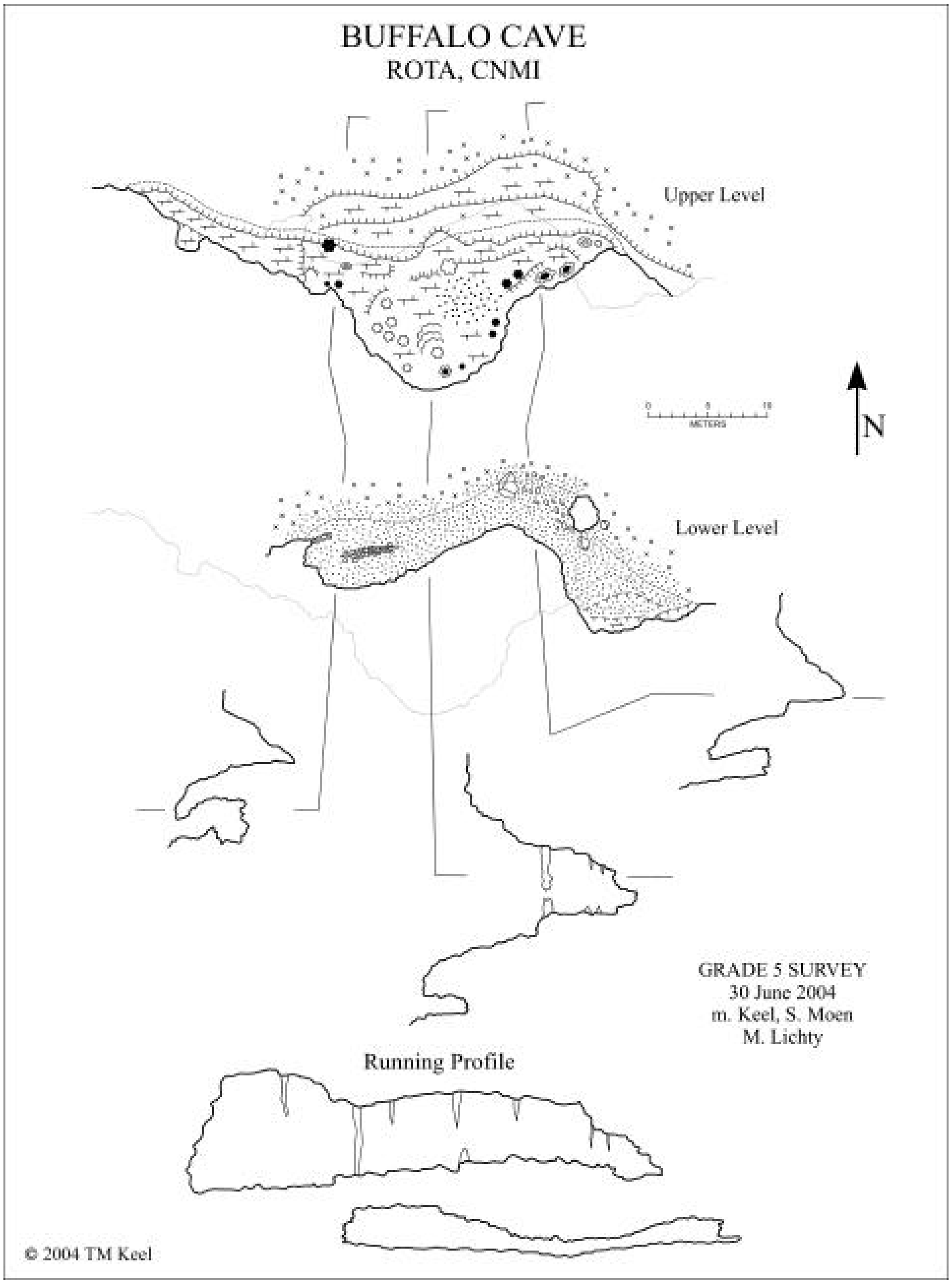

Figure 233: Map of Buffalo Cave

Exception Cave

Exception Cave is located less than 2 m below the cliff top at *Duge*, south of *Puntan Fina Atkos*. The cave is the remaining "half" of a wide, flat chamber that has been partially removed by cliff failure. The entrance is not visible from the cliff top but is accessible by climbing down from the top to the north end of the cave. The entrance, at about 2 m high and 25 m across, is the longest part of the cave and is clearly visible from the coast below. The ceiling averages about 2 m but drops toward the rear of the cave. The width of the cave varies from 5 to 10 m. Exception Cave is highly decorated with speleothems, although they are somewhat weathered due to the exposed nature of the cave. In contrast to many of the other caves documented on Rota, Exception Cave shows very little to no apparent lithologic control on its morphology and development.

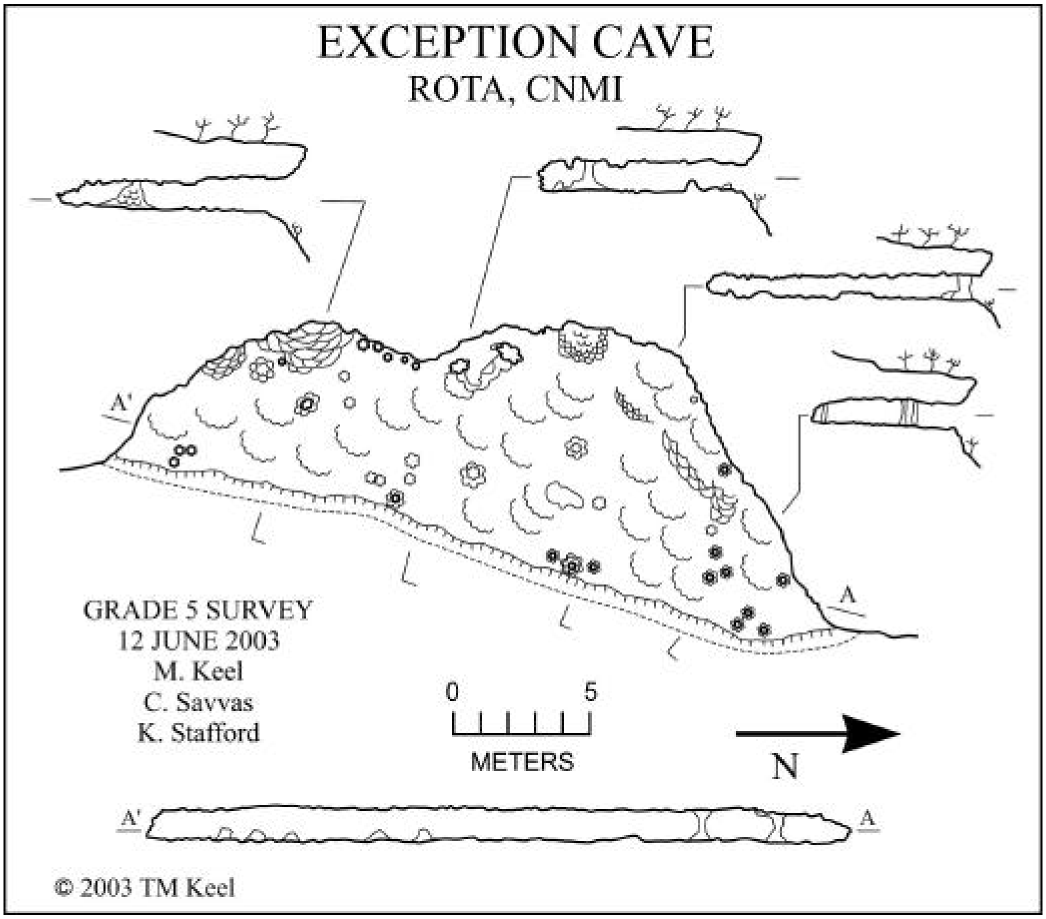

Figure 234: Map of Exception Cave

Fisherman Cave

Fisherman Cave is located northeast of the Swimming Hole on Rota's north coast at about 1 m above sea level. Fisherman Cave is roughly shaped like an "8" oriented northeast-southwest, with two entrances on the northwest side. The cave is about 19 m long and floored mainly with loose cobbles and boulders.

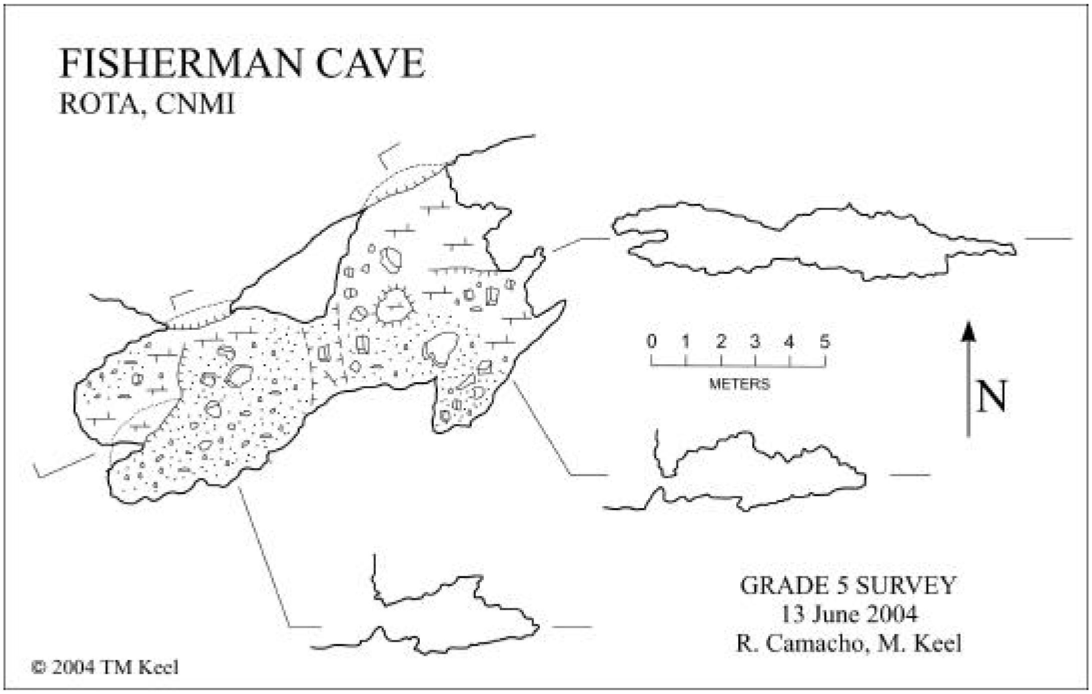

Figure 235: Map of Fisherman Cave

Hourglass Cave

Hourglass Cave, at about 40 m elevation, is part of a complex of caves around *Liyang Finta*, in a notch in the cliff between *I Koridot* and *Taksunok*. It is at about the same elevation as *Liyang Finta* on the east wall of the notch and is reached by a short horizontal traverse across the cliff face. The south part of Hourglass Cave is about 1 m high, 2 m wide tapering to zero and about 6 m long. This south part of Hourglass Cave has a high density of flowstone columns that are highly weathered due to complete exposure. The north part of Hourglass is about 2 m high, 4 m wide and extend about 5 m back from the drip line. This part of Hourglass has evidence of resolution of speleothems. Hourglass Cave is apparently a flank margin cave remnant.

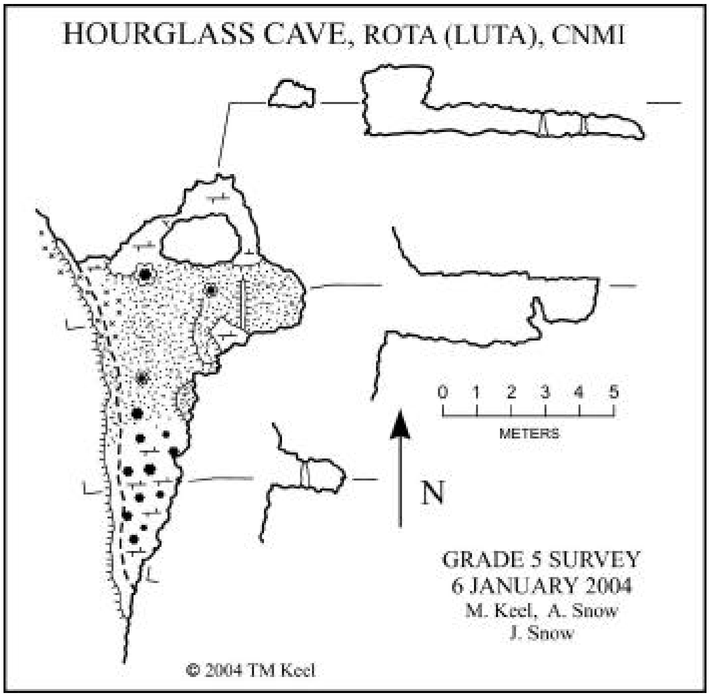

Figure 236: Map of Hourglass Cave

Liyang Ayuyu

Liyang Ayuyu is located at the west end of the isolated cliff line about 500 m directly north of the parking area of the *Chenchon* Bird Sanctuary. *Liyang Ayuyu* is developed in limestone with a strong expression of dipping fore-reef beds. The entrance area of *Ayuyu* is about 17 m wide and about 7 m tall. The cave extends back about 22 m back from the drip line. About 8 m back into the cave, it narrows irregularly to about 6 m. The floor of the cave is primarily cobbles on top of the stepped exposure of the depositional beds.

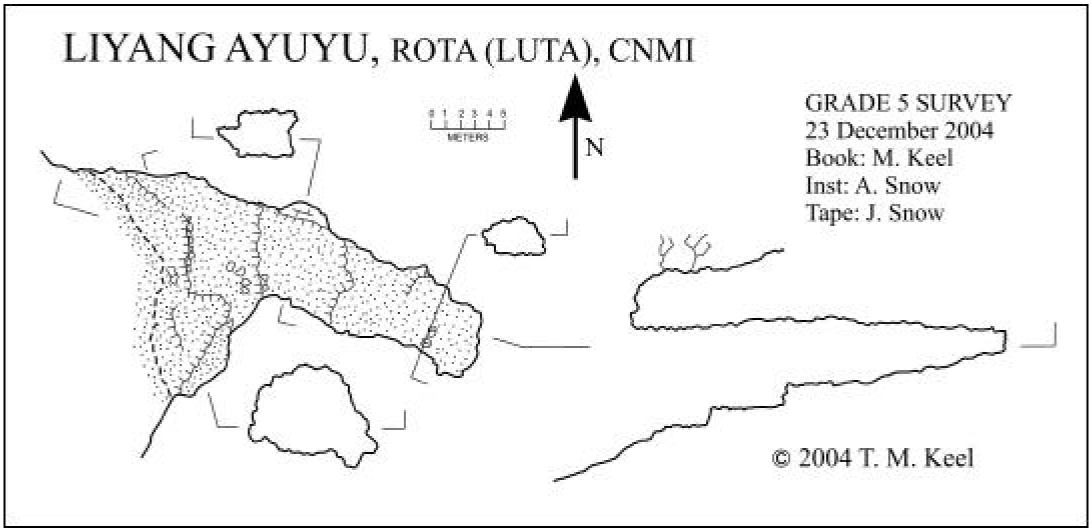

Figure 237: Map of Liyang Ayuyu

Liyang Chenchon

Liyang Chenchon is located at about 90 m elevation near *I Koridot* in the *I Chenchon* area. The entrance is two holes that drop into the north end of a low wide room which slopes away to the south. This room is about 7 m by about 5 m. At the south end this room opens into a larger room, about 10 m long by about 8 m wide, that continues to slope at about the same grade. The floor at the north and south edges of this larger room drops away but no passable leads were found.

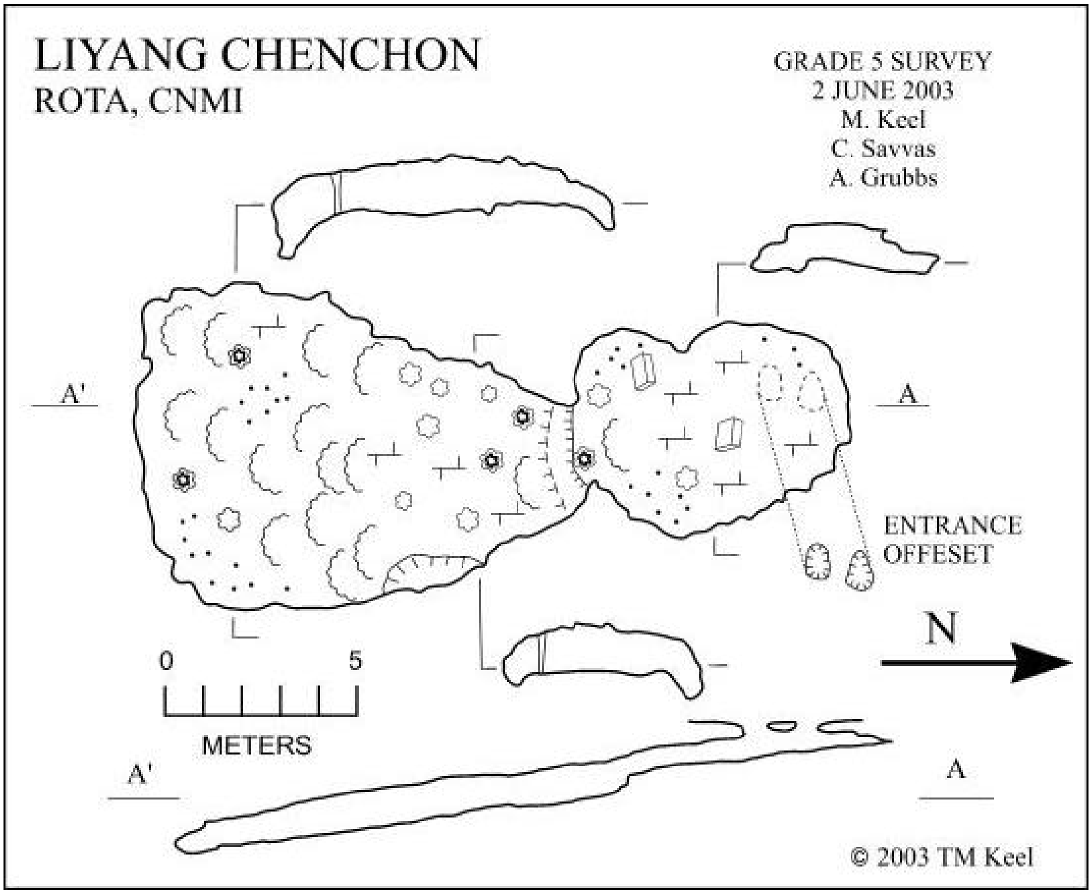

Figure 238: Map of Liyang Chenchon

Monkey Cave

Monkey Cave, located at about 25 m elevation, is part of a complex of caves around *Liyang Finta*, in a notch in the cliff between *I Koridot* and *Taksunok*. It is at the base of the east wall of the notch about 30 m south of Basement Cave. Monkey Cave has a combination of the morphologies seen if flank margin caves and in mixing zone fracture caves. Monkey Cave is about 13 m wide at the entrance and extends back a total of about 24 m from the drip line. The entrance area slopes irregularly down to the south, into a room about 8 m wide and about 10 m long. Leading from the north side of this room is a linear passage 1-2 m wide and about 2 m high. The floor of this passage slopes to the south and the ceiling pinches into a crack. At about 5 m in, this passage widens to about 3 m where there is a small hole leading to a roughly circular room with a cobble and sand floor. On the west wall of this room is a small "port hole" into a very small chamber that has sunlight entering through an impassable linear passage from the entrance area. From the south side of this room leads a crawlway that leads back to the entrance area. The total surveyed length is about 45 m.

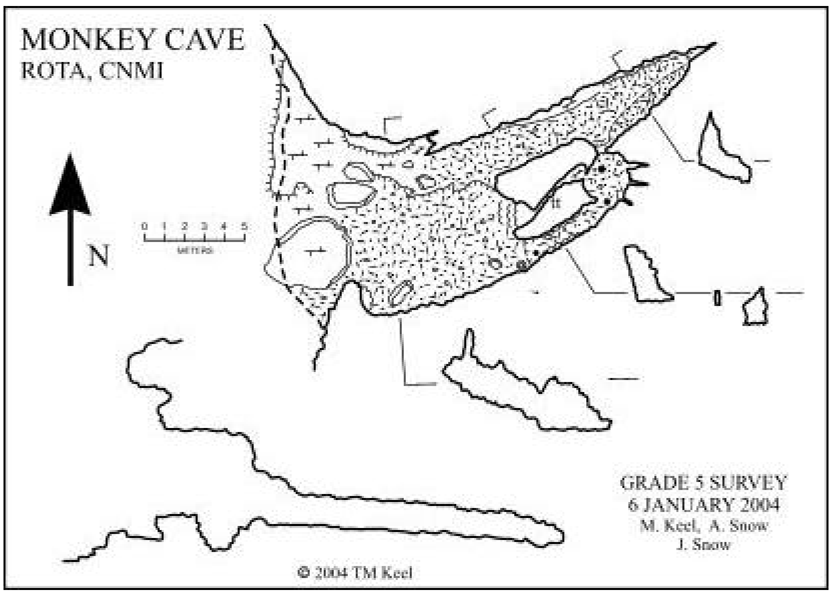

Figure 239: Map of Monkey Cave

Not Much Cave

Not Much Cave is located on the nearly level bench, north east of Pictograph Cave, near the Banyan Complex. Not Much Cave is developed along the same conjugate joint set as the Banyan Complex but was surveyed separately. Not Much

Cave consists of a small vertical shaft about 2 m deep, about 3.5 m long and about 1 m wide. The long axis of the feature is oriented to the northeast. At the southeast end of the feature there is a vertical section of intact bedrock that reaches from ground level almost to the floor of the feature.

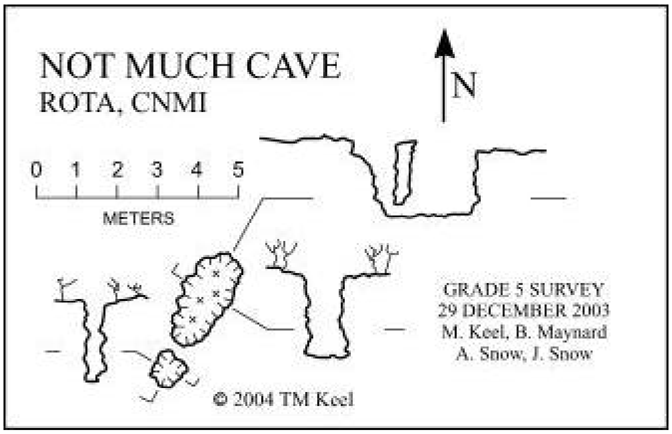

Figure 240: Map of Not Much Cave

Reyes Flank Margin Cave Complex

This horizon of flank margin cave remnants is located at about 120 m elevation, northwest of *Taksunok*, near *I Chenchon*. The complex consists of several, mostly open flank margin cave remnants not encompassed by the same drip line. The southernmost section is about 30 m long and about 4 m wide. The next section to the north is almost 40 m long and about 4 m wide. The next two sections to the north are much smaller and partially enclosed. Continuing to the north, there are three more open sections 13 m, 5 m, and 20 m long. The complex contains a large amount of human modification, primarily stone walls, built up floors and steps. The cliff face and most of the cave walls show distinctive fore-reef beds. In the middle part of the complex are two chambers that are more enclosed, supporting the idea of flank margin cave development followed by later breaching and wave driven modification. The different sections of this complex are predominantly at the same elevation indicating that they probably all developed during the same sea level still-stand. Southeast of the complex there are more flank margin remnants that are not tied in to this survey.

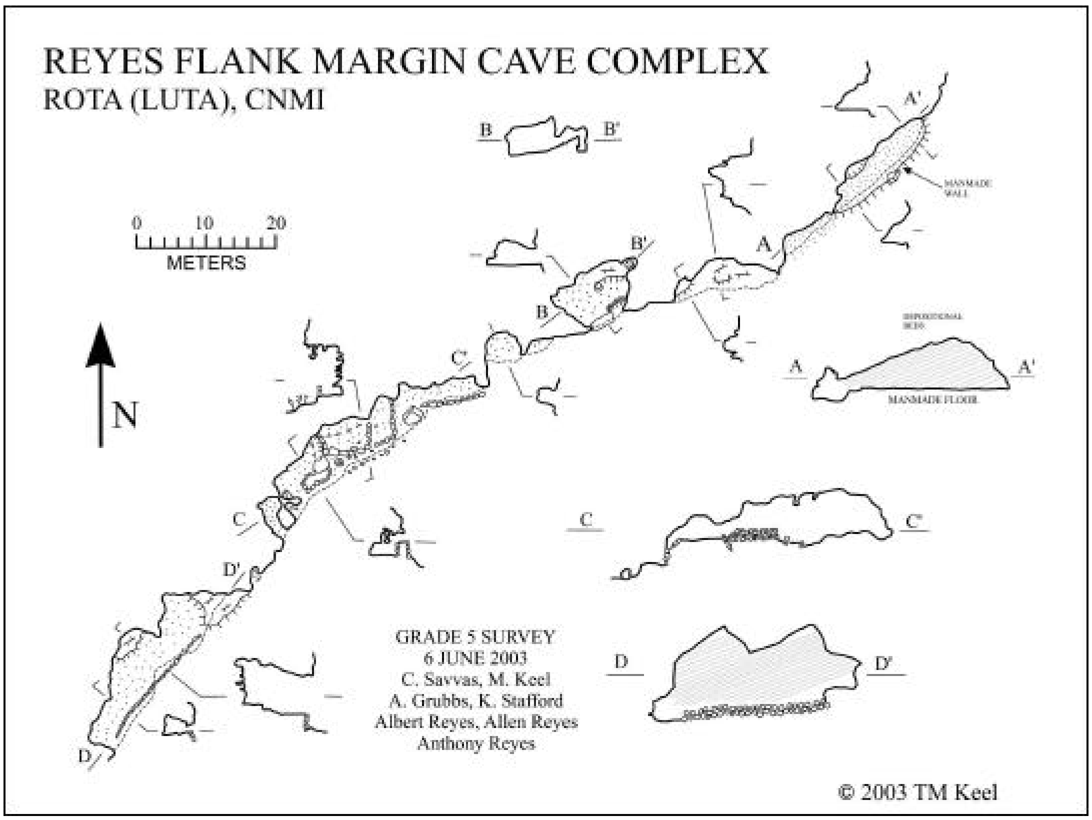

Figure 241: Map of Reyes Flank Margin Cave Complex

Ripple Cave

Ripple Cave is a flank margin cave located about 2 m above sea-level on the coast at *As Dudo.* The entrance to Ripple Cave faces just east of south and the main axis of the cave (17 m) is on the same orientation. The plan of Ripple Cave is roughly ovoid and it is about 11m wide. The floor of most of the cave is bare limestone and the ceiling height is about 1-1.5 m. Two large boulders dominate the center of the cave. One of these boulders reaches the ceiling. Ripple Cave is named for the well preserved wave(?) ripples that are eroded out in relief on both sides of the entrance.

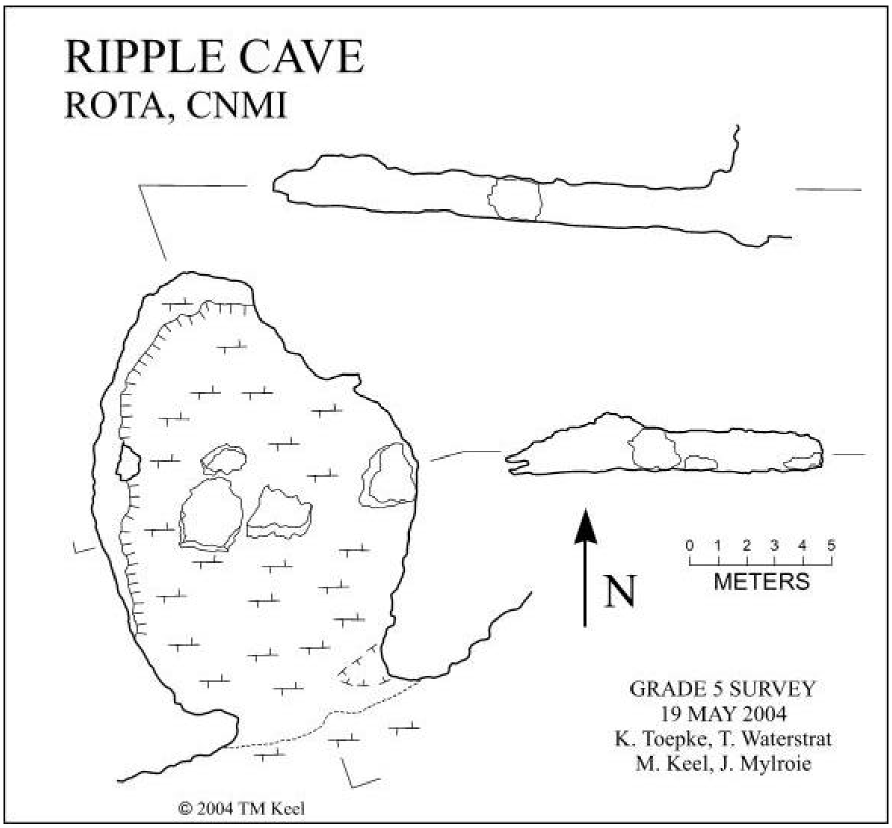

Figure 242: Map of Ripple Cave

Surge Cave

Surge Cave is a complex feature, located on the coast at *As Matmos*, that is apparently the remnant of a flank margin cave, the development of which was influenced by two fractures the extend to the coast. The main section of this feature is an open depression that slopes up to the southwest, grading into the elevation of the coastal cliff. On the northeast side of the depression, where it is about 5 m deep, there is an arch through the coastal cliff out to the sea level bench. The pool under this arch is tidal and connect to the ocean via one open channel and one passage below sea level. Both connections are apparently developed along fractures. Just inland from the arch, below the floor of the depression is a partially collapsed flank margin chamber no more than 1 m high but several meters in horizontal extent. Parts of the lower chamber were not enterable due to waves.

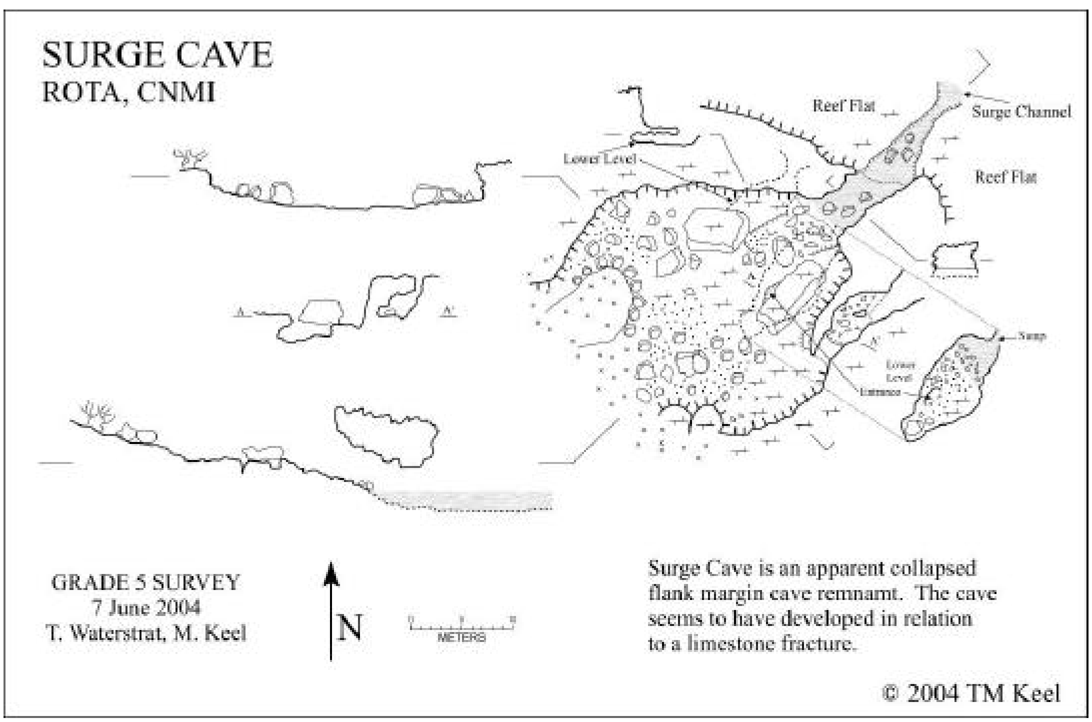

Figure 243: Map of Surge Cave

The Swimming Hole

The Swimming Hole is located along the north coast of Rota, about 2.5 km northeast of the Coconut Village Hotel and is easily accessible by the road that runs past the hotel. The Swimming Hole is a roughly oval, water filled depression within the tide zone, but is protected from the surf by raised reef rocks on the north side. The coastal (north) end of the Swimming Hole is covered in loose boulders and sand down to the water, while most of the floor of the depression is covered in sand. There are two large rocks slabs adjacent to the south side of the depression and one adjacent to the north side. The north end of the depression is overhung by at least a few meters but was not fully explored. An unpublished, scaled drawing obtained from Edgar Tuazon at Dive Rota was used in conjunction with survey data to construct a map of the Swimming Hole showing the underwater connection to the ocean The lip of the depression on the east and west sides, adjacent to the deep overhang on the north, are overhung by about 0.3 m. The large slabs near these lips appear to have once been part of a ceiling. Fresh water discharges into the coastal end of the Swimming hole and at a few places to the east. It is hypothesized that the Swimming Hole is a collapsed flank margin cave and somewhat analogous to the caletas of the Yucatan, Mexico (Back et al., 1984).

Taisacana Museum (*Antigo*) Cave *Taisacana* (*Antigo*) Museum Cave is located beside the main highway, about 1.5 km northeast of *Songsong* Village, at *Esong*. The entrance to the cave is covered by doors under a building that is built above the entrance. The first 30 m of the cave consists of a linear room variably 5 m wide and starting at 2.5 m high rising to about 10 m. Beyond 30 m the cave widens into a room 25 m by 18 m by about 12 m high, with the long axis orientated the same way as the entrance passage. At the back of the larger room, a short climb-up leads to a tall narrow room that pinches down to an impassable crack. The floor 108 of the most of the cave is packed soil. The trend of the entire cave is along a fracture that strikes at 154°. The fracture along which the cave is developed is prominent in the ceiling for most of the length of the cave. The cave is a privately owned museum and houses an extensive collection of artifacts from the Chamorro, Spanish, German, Japanese, and American eras of Mariana Islands history.

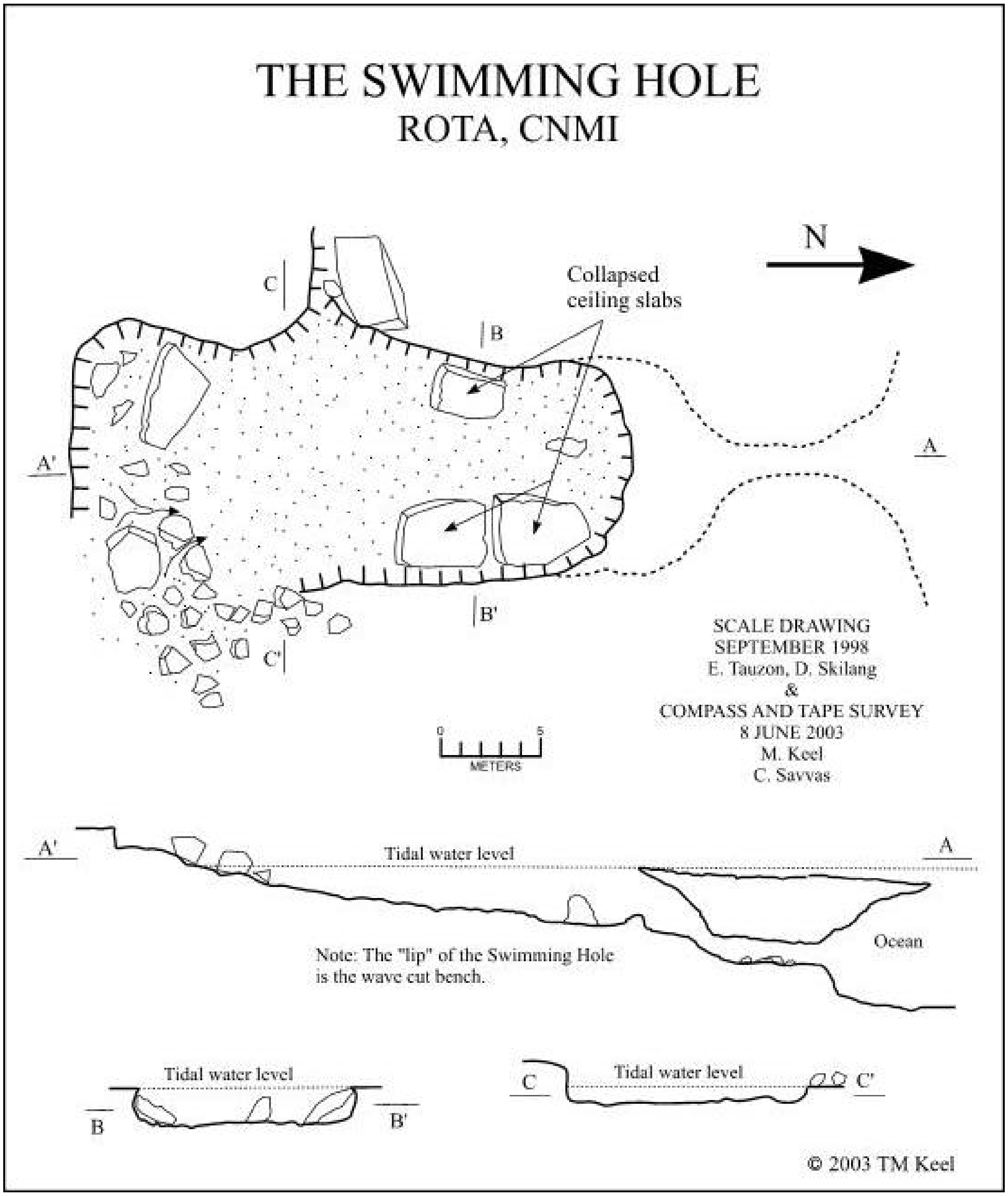

Figure 244: Map of The Swimming Hole

Fissure Caves

Banyan Complex

The Banyan Complex is located on the nearly level bench, north east of Pictograph Cave. The Banyan Complex consists of several small cave features (not all of which were surveyed) developed along an apparent conjugate joint set. Most of the cave features in the Complex are small vertical shafts about 2 m deep and about 1 m in diameter. The cave on the northern part of the mapped portion of the Complex is about as deep as the other features but also has about 4 m of passage.

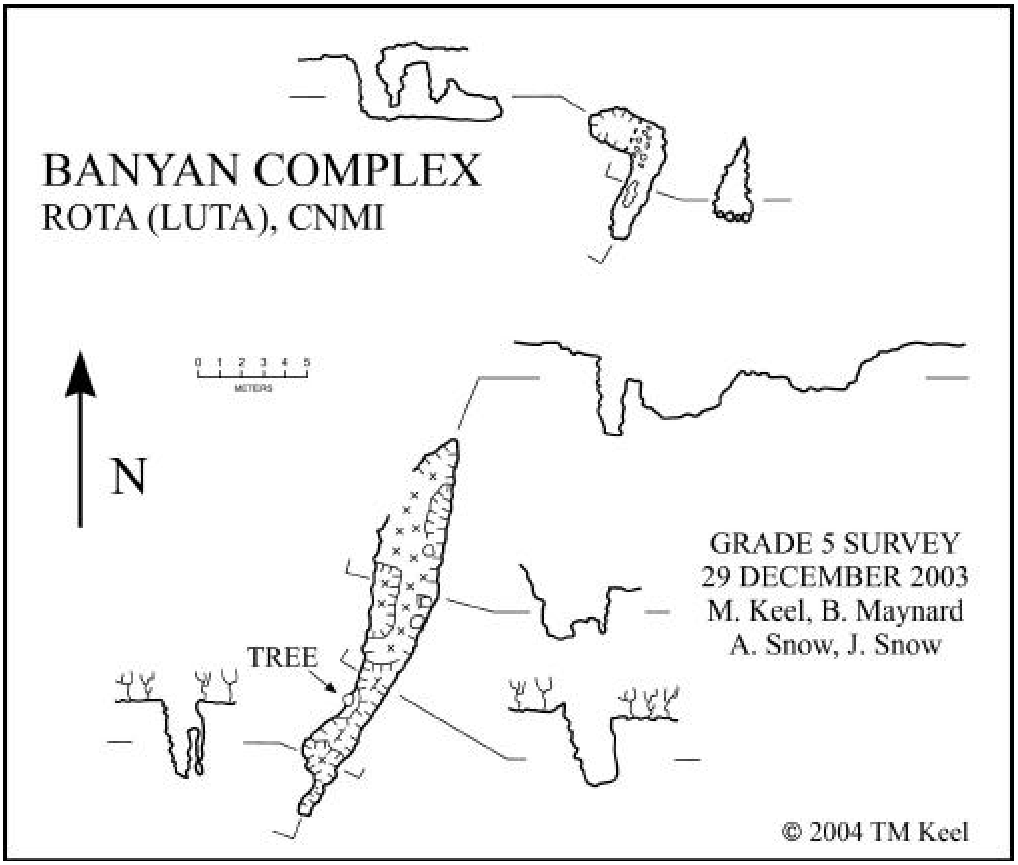

Figure 245: Map of Banyan Complex

Even Smaller Cave

No information, other than the fact that exists, was provided for Even Smaller Cave in Keel (2005); however, Keel provided enough information (location and Walls data plot) in a personal conversation to be able to determine that Even Smaller Cave is a fissure cave in the *Sabana* Region.

Mermaid Cave

There is no map or description of this small flank margin cave in Keel (2005). However, the location data and a copy of the original sketch map provided by T. M. Keel allowed me to determine that Mermaid Cave is a fissure cave in the Sinapolo Region of Rota.

Slab Cave

Slab Cave is located at the base of the cliff, north of the complex of caves around *Liyang Finta* at about 30 m elevation. Slab Cave is a talus cave produced by simple cliff margin failure and has very little solutional modification. Slab Cave is about 10 m long with a slight bend near the middle and is open at both ends. The floor is composed of loose rocks and vegetation that have accumulated in the bottom of the fracture. The height of the cave is difficult to determine because the detached slab is nearly parallel to the remaining cliff face.

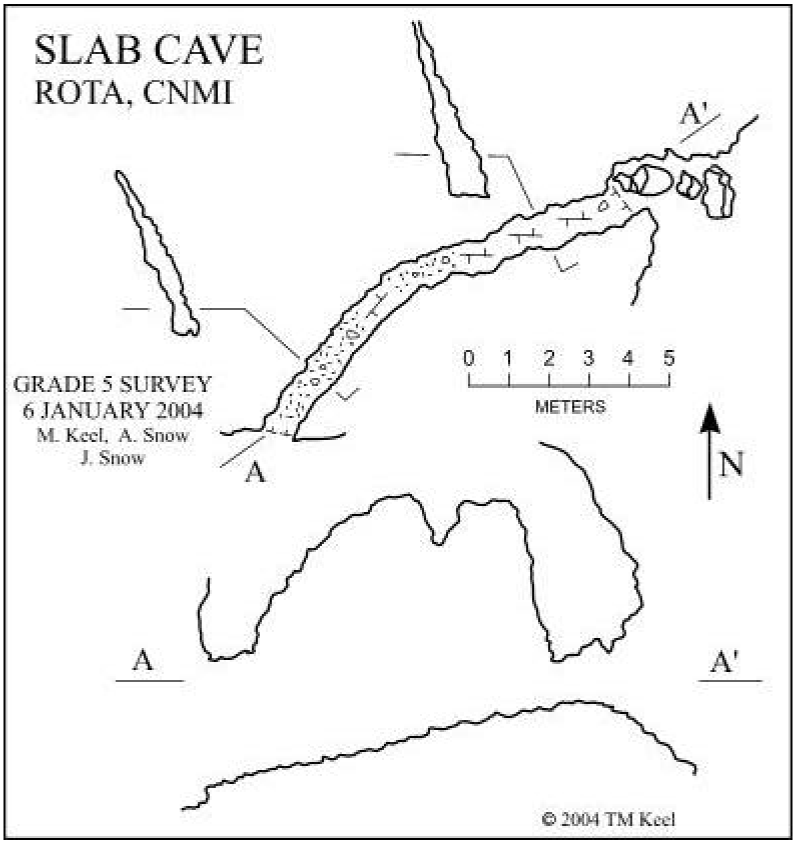

Figure 246: Map of Slab Cave

Mixing-zone Fracture Caves

Arrowhead Cave

Arrowhead Cave is one of several linear caves located in the cliff base, north of the *Chenchon* Bird Sanctuary overlook. This 50 m long cave is obviously developed along a bedrock fracture. The floor of the cave is nearly level and covered with loose soil, probably including old guano. The entrance to Arrowhead Cave is about 13 m wide and about 17 m high. About mid-length of the cave it is only about 4 m wide and narrows to 1-2 m before ending abruptly. The crack along which the cave is developed in prominent along the length of the ceiling. In one place, the ceiling crack is so high that an estimate of the ceiling height was not possible.

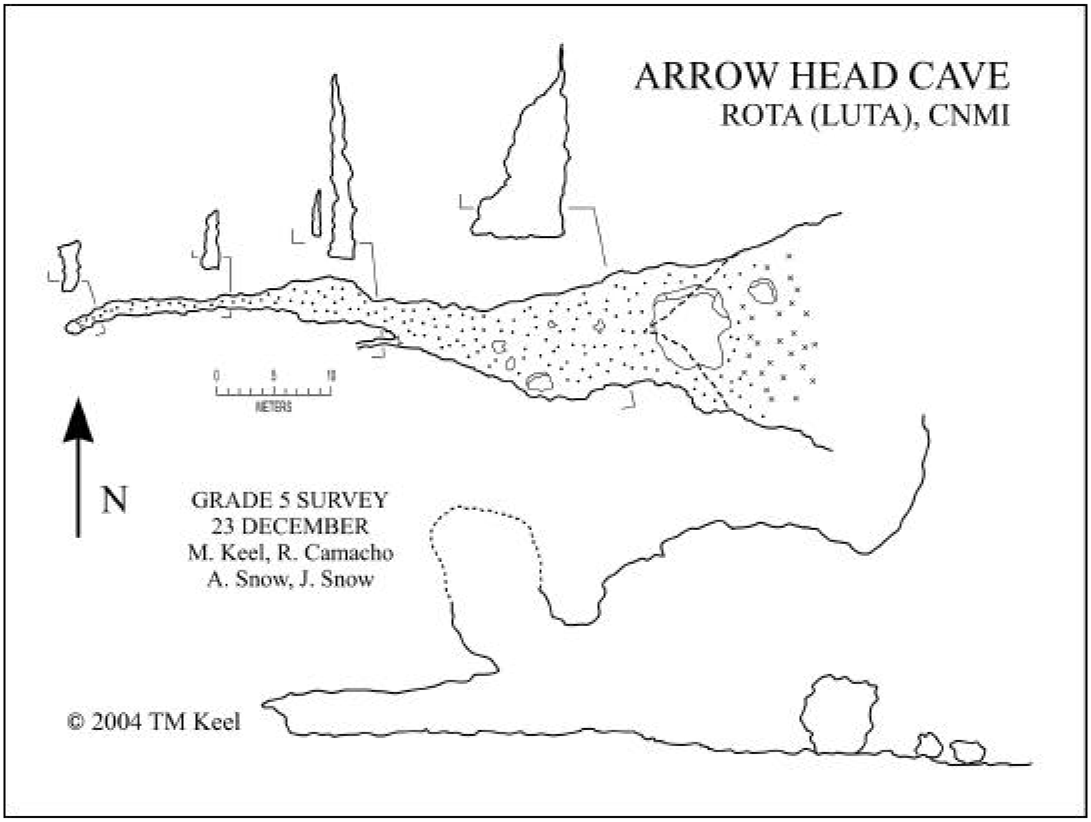

Figure 247: Map of Arrow Head Cave

Basement Cave

Basement Cave is located just below *Liyang Finta*, a fracture cave at 50 m elevation, and is apparently developed along the same fracture. Airflow detected in *Liyang Finta* was probably coming up from Basement Cave. Basement Cave only extends about 6 m back from the drip line. It is about 3 m high at the drip line but closes to about 2 m at the rear. The cave appears to have possibly developed by boulders and cobbles filling a fracture, becoming cemented, then some of this bouldery facies material being removed.

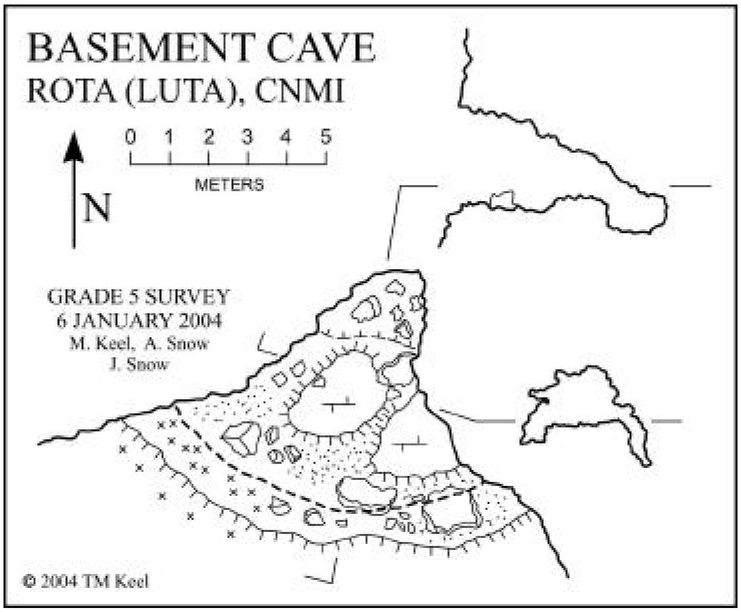

Figure 248: Map of Basement Cave

Birthday Cave

Birthday Cave is one of a cluster of four linear caves located at about 30 m elevation, in the cliff face inland from *Puntan As Fani*, south of *Fina' Atkos*. Birthday Cave is about 13 m long and developed along an obvious fracture that is expressed in the ceiling of the cave for its full length. For most of its length, Birthday Cave is about 2-3 m wide and 7-8 m high. The floor of the cave is very flat and covered with soil with a few boulders near the entrance.

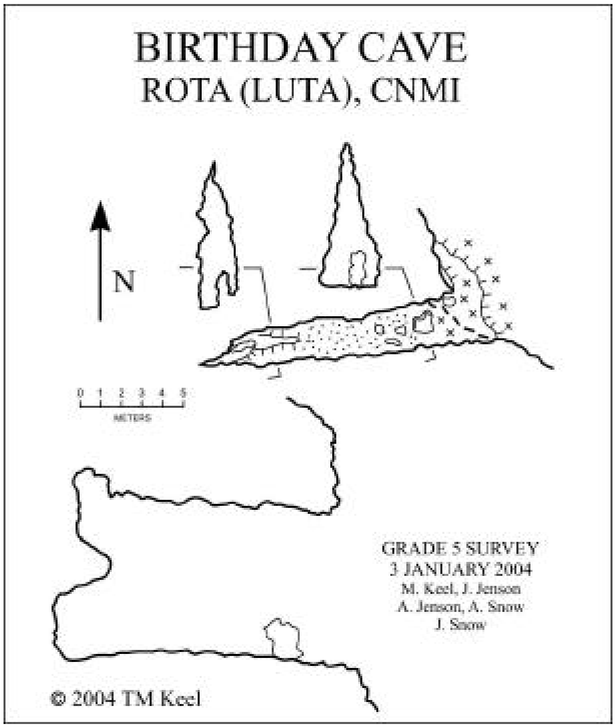

Figure 249: Map of Birthday Cave

Bonus Cave

Bonus Cave is located at about 30 m elevation, about 1 km east of the end of the road at *As Matmos* and is the first of three large cave entrances along this section of cliff face. The entrance is visible as a 20 m tall cleft in the cliff face. The cave consists primarily of one large passage 10-20 m high and 6-8 m wide running at about 280 degrees for about 100 m. The passage ends with a small room and some bedrock "bone yard". The "bone yard" is believed to be similar to cave "sponge work" documented by Palmer (1991) and is thought to indicate an aggressive dissolutional environment. Bonus cave is developed along an obvious linear fracture in the bedrock. Along the lower walls in some parts of the cave are "curbs" of what appear to be bedrock sticking out about 0.25 m from the wall and running horizontally for several meters.

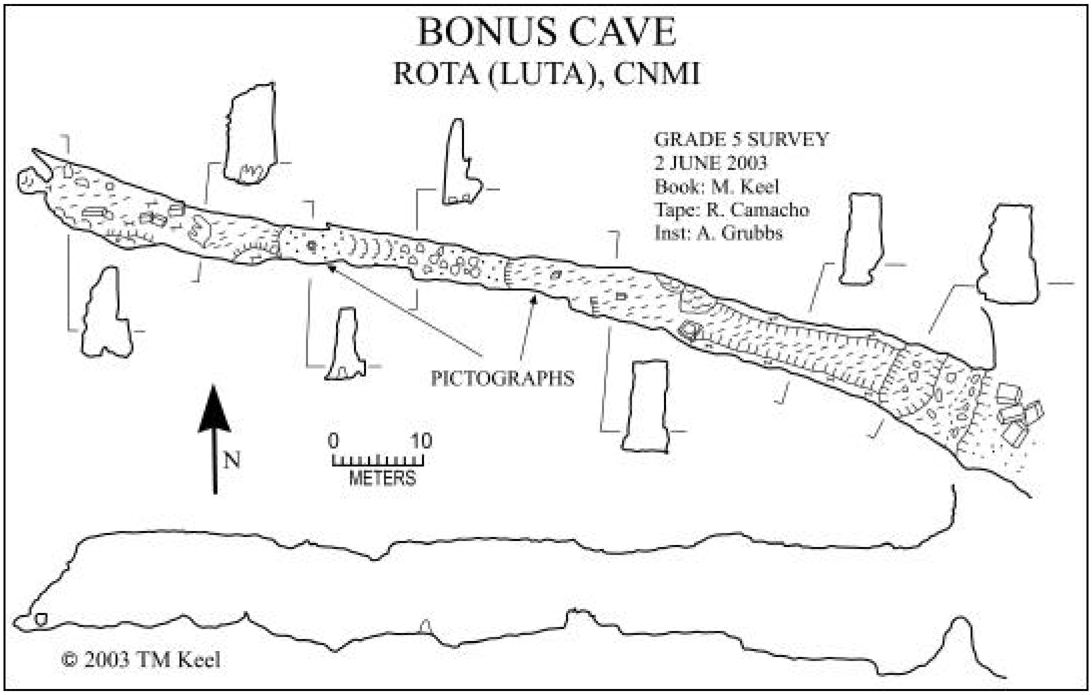

Figure 250: Map of Bonus Cave

Delia Cave

Delia Cave is one of three large entrances located in a series of breaks in the cliff face below *I Koridot*. Of the other two entrances, one is not safely reachable and the other is only a remnant of a cave, which was not mapped. *Delia* Cave extends for about 40 m into the cliff face from the drip line. The floor of *Delia* cave is a very steep series of vertical offsets and slopes, making the cave about as tall as it is long. The main section of *Delia* Cave is about 7 m wide and has a large skylight about 17 m back from the drip line. To the left of the main section of the cave is a small parallel section containing deep deposits of apparently old guano.

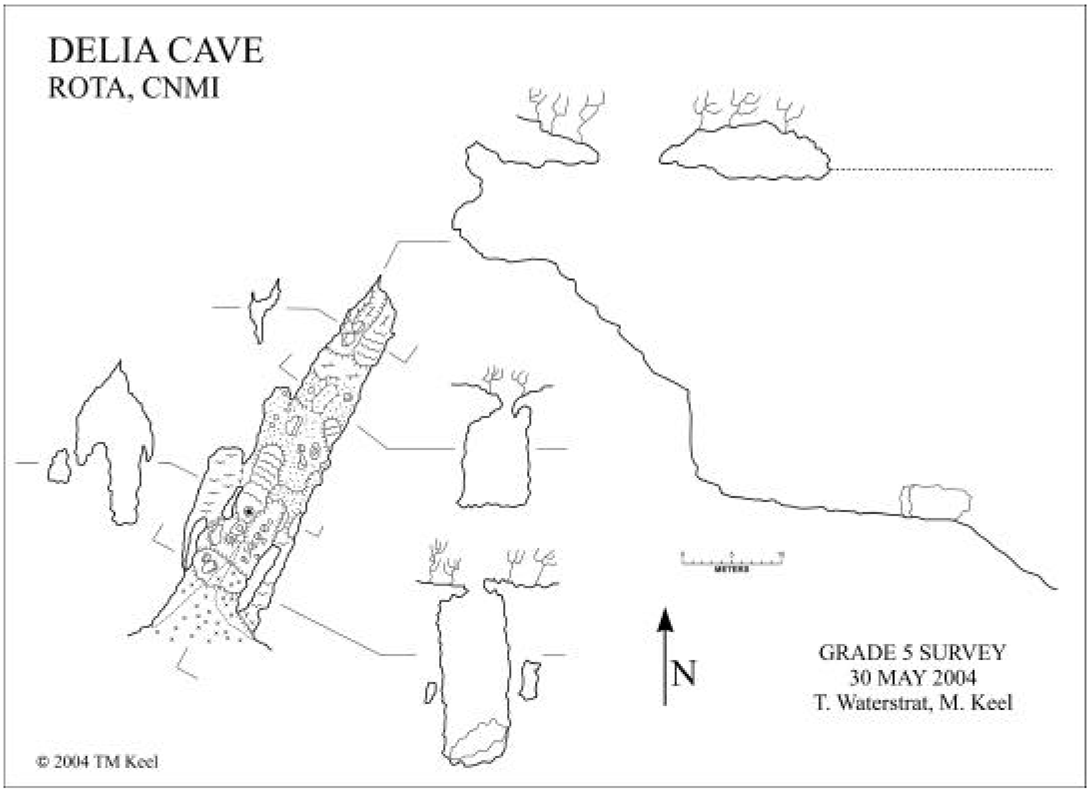

Figure 251: Map of Delia Cave

Forked Cave

Forked Cave is one of a cluster of four linear caves located at about 30 m elevation, in the cliff face inland from *Puntan As Fani*, south of *Fina' Atkos*. Forked Cave is the second cave from the north. Forked cave, which is developed along an obvious fracture, is boulder floored at the 10 m tall, 8 m wide entrance. The passage narrows gradually to about 3 m at about 20 m in. Then the cave widens to about 7 m before it splits into two short passages that both end at impassable fractures.

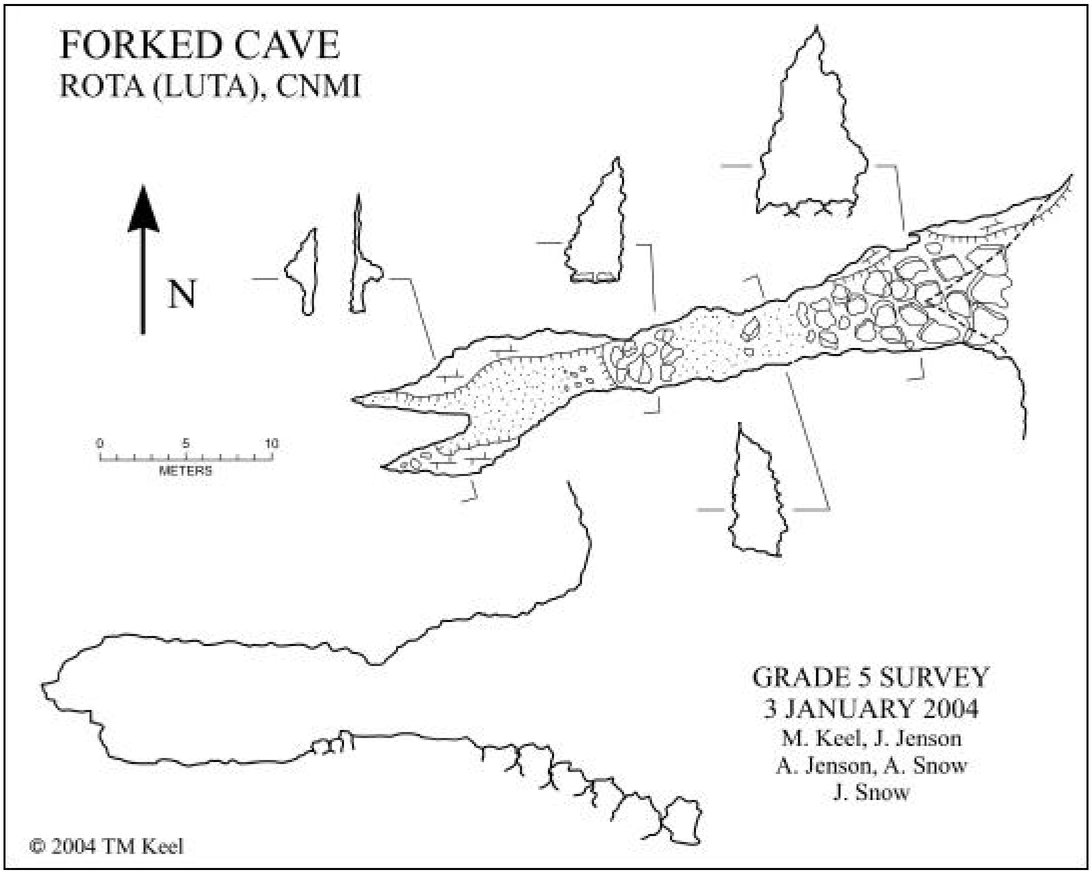

Figure 252: Map of Forked Cave

Honey Comb Cave

Honey Comb Cave is one of a cluster of four linear caves located at about 30 m elevation, in the cliff face inland from *Puntan As Fani*, south of *Fina' Atkos*. Honey Comb Cave is the second cave from the south and was so named because of the conspicuous bee hives very high in the entrance. While the entrance to Honey Comb is 10 m tall and 10 m wide, the cave only extends back from the drip line about 8 m. Like the other caves in this group. Honey Comb is developed along an obvious fracture. The floor in the entrance is dominated by one large boulder but the rest of the floor is covered with soil plus a few cobbles.

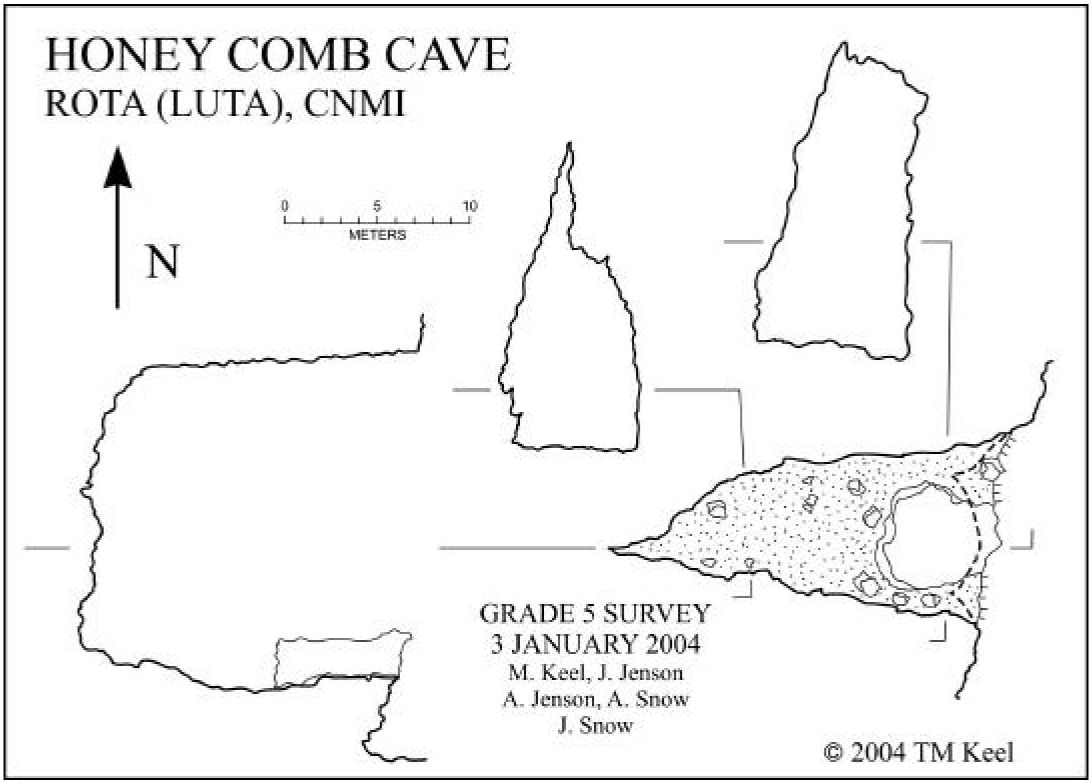

Figure 253: Map of Honey Comb Cave

Honey Eater Cave

The entrance to is the large hole in the south wall of the cove at *As Dudo.* The cave is reached by a difficult climb over friable limestone, inside the drip line. The entrance to Honey Eater Cave is at the west end of the large overhang. The entire overhang was not survey due to the presence of a very large beehive. The more enclosed part of the cave was safely entered and mapped. Honey Eater Cave extends back about 20 m from the drip line. The main section of the cave is about 10 m wide and about 5 m tall. The walls of the main chamber of Honey Eater Cave exhibit cusps that suggest phreatic dissolution. From the south side of the main section extends a passage that quickly narrows to impassable. This small passage can be seen to continue for several meters. Except for a 4 m diameter, 3 m high mound of limestone, the entire floor of Honey Eater Cave is covered with guano. The guan is at least 0.5 m deep in some places.

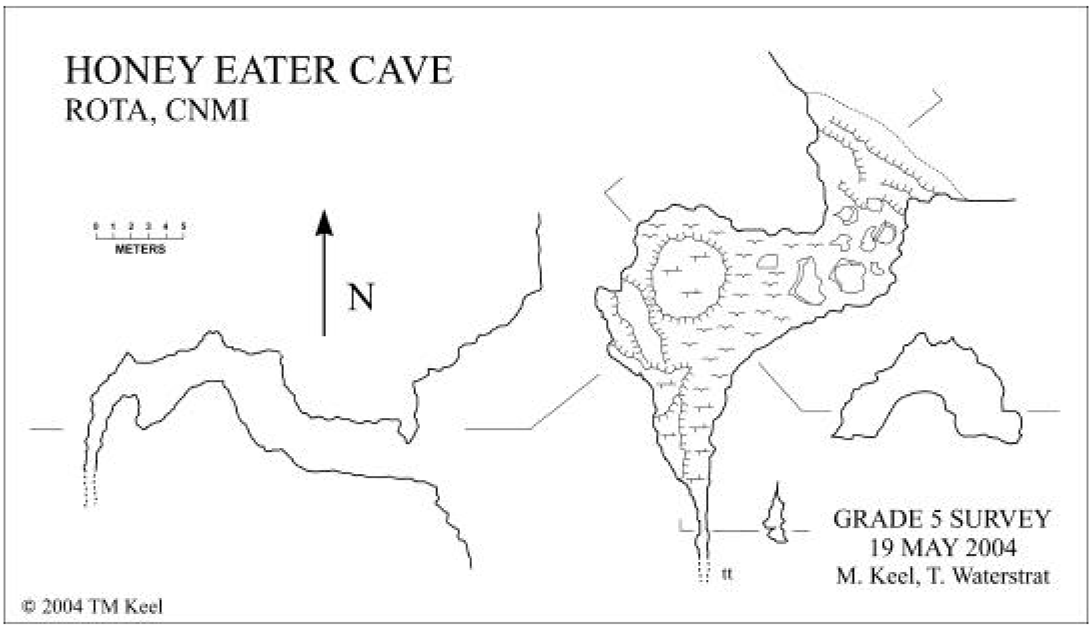

Figure 254: Map of Honey Eater Cave

Knuckle Bone Cave

Knuckle Bone Cave is located at about 30 m elevation near *Puntan Fina Atkos*, about 1 km east of the end of the road at *As Matmos*. Knuckle Bone is the middle of three large linear caves along this stretch of cliff. The area just outside the entrance to Knuckle Bone is dominated by a large block of rock that may be an in place bedrock remnant or collapsed boulder. The drip line of Knuckle Bone Cave runs diagonally across the entrance to the cave from southeast to northwest. The cave is composed of two passages that lead from the entrance. The shorter, southern passage extends back about 60 m from the drip line and ends in solutionally modified cracks. This southern passage is about 5 m wide tapering toward the rear and is about 10 m high at the drip line and tapers irregularly to about 4 m high near the end. The ceiling of this passage narrows into a crack for most of its length. The northern passage extends about 70 m back from the drip line, and is about 5-6 m wide back to about 45 m where it widens to the south to about 10 m. The southern wall of this part of the cave appears to be coincident with the southern passage of the cave, indicating that it is related to the fracture along which the southern passage is developed. The floor of the northern passage of Knuckle Bone Cave drops at about 10 m from the drip line, giving a ceiling height of about 12-14 m for most of its length.

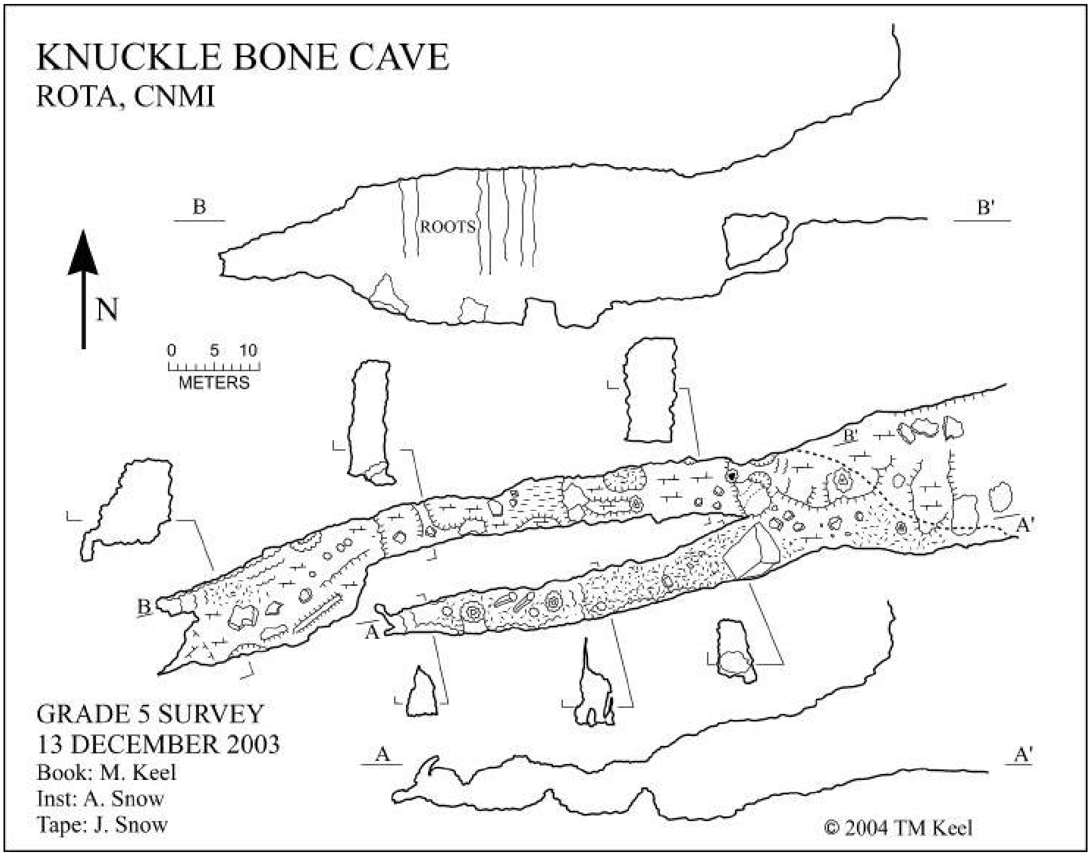

Figure 255: Map of Knuckle Bone Cave

Letterman Cave

Letterman Cave is the smallest of several linear caves located in the cliff base, north of the *Chenchon* Bird Sanctuary overlook, between *Liyang Paluma* and *Liyang Lu'ao.* Letterman Cave is about 8 m long, 2-3 m wide and about 4-5 m high. The entrance to Letterman Cave is partially blocked by a boulder. The floor of the cave is mainly soil with a few cobbles.

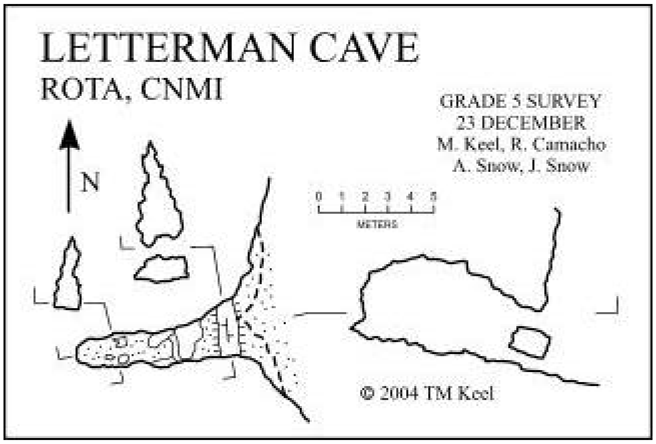

Figure 256: Map of Letterman Cave

Little S Cave

Little S Cave is located on the west wall of the cove at *As Dudo.* The cave is developed along a fracture that trends northeast-southwest. The entrance to Little S Cave faces northeast and is reached by a 2 m climb. The cave is about 1.5 m wide for the first 5 m, then widens to about 6 m. The rear of the cave has an inverted "T" profile, developed along the genetic fracture. Little S Cave is about 25 m long.

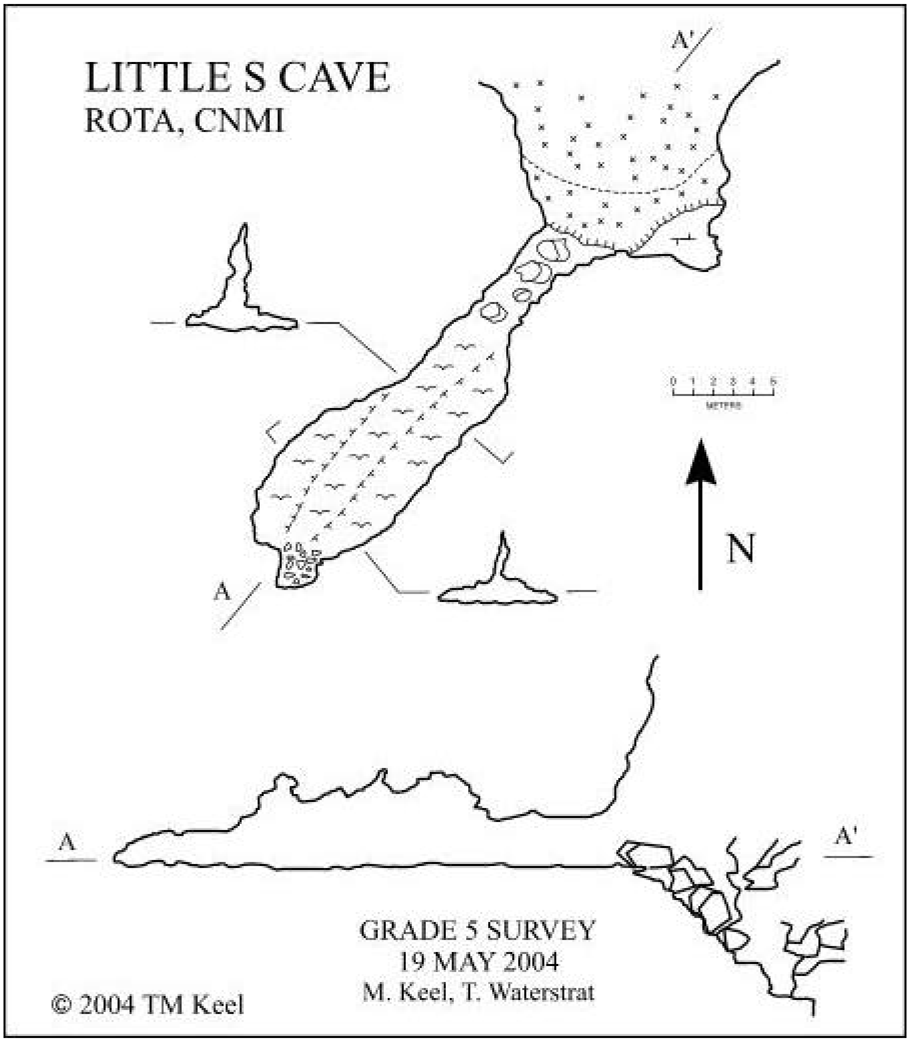

Figure 257: Map of Little S Cave

Liyang Apaka'

Liyang Apaka' is the southernmost and largest cave in a cluster of four linear caves located at about 30 m elevation, in the cliff face inland from *Puntan As Fani*, south of *Fina' Atkos*. The entrance to *Liyang Apaka*' is about 13 m wide and 17 m tall. The passage continues at about this size to a dramatic ceiling drop about 18 m into the cave. For about 3-4 m the ceiling is around 1.5 m high before it suddenly increased to about 9 m then drops irregularly toward the rear of the cave. The total length of *Liyang Apaka*' is over 60 m. It ends at a small impassable passage at floor level. *Liyang Apaka*' is developed along a fracture that is evident at the entrance and at the rear of the cave but not at the low ceiling point near the middle. The floor of *Apaka*' is covered mostly with cobbles and boulders in the outer section and with soil and guano in the middle and rear.

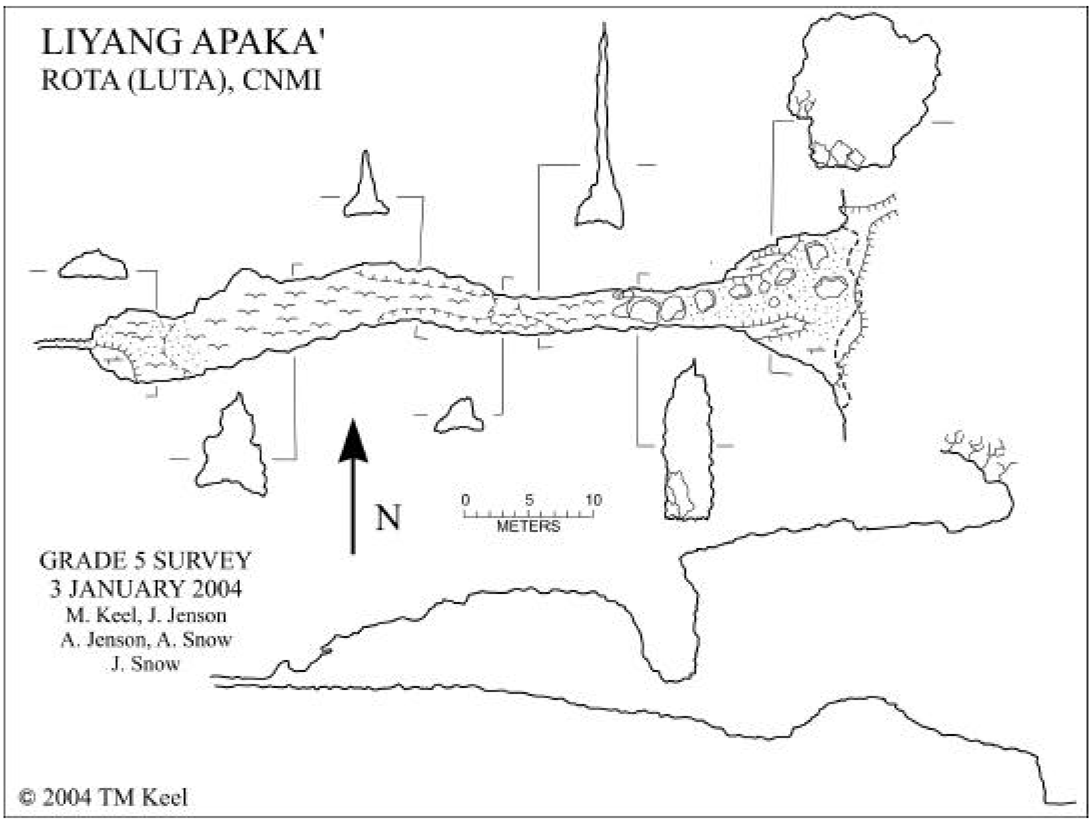

Figure 258: Map of Liyang Apaka'

Liyang Botazon

Liyang Botazon is located at *Fina' Atkos*, below the steep canyon that cuts across several terraces and opens at sea level. The entrance is about 50 m wide and about 15 m tall. About 10 m from the drip line, there is a large skylight about 15 m across that spans most of the width of the cave. The entrance area of *Botazon* is mostly covered with very large boulders with bedrock exposed in a few places. At about 20 m from the drip line the cave narrows to about 10 m and then gradually narrows toward the back of the cave. The ceiling stays at about the same level but the boulder covered floor gradually climbs such that the passage is about 10 m high before it pinches down at the end of the cave. *Botazon* has a few short side passages that are apparently developed along fractures. The entire cave is coincident with the surface canyon that cuts across the terraces above the cave. This entire *Fina' Atkos* notch-steep canyon-*Liyang Botazon* complex is developed along what appears to be a significant fault, although no positive evidence of displacement was identified.

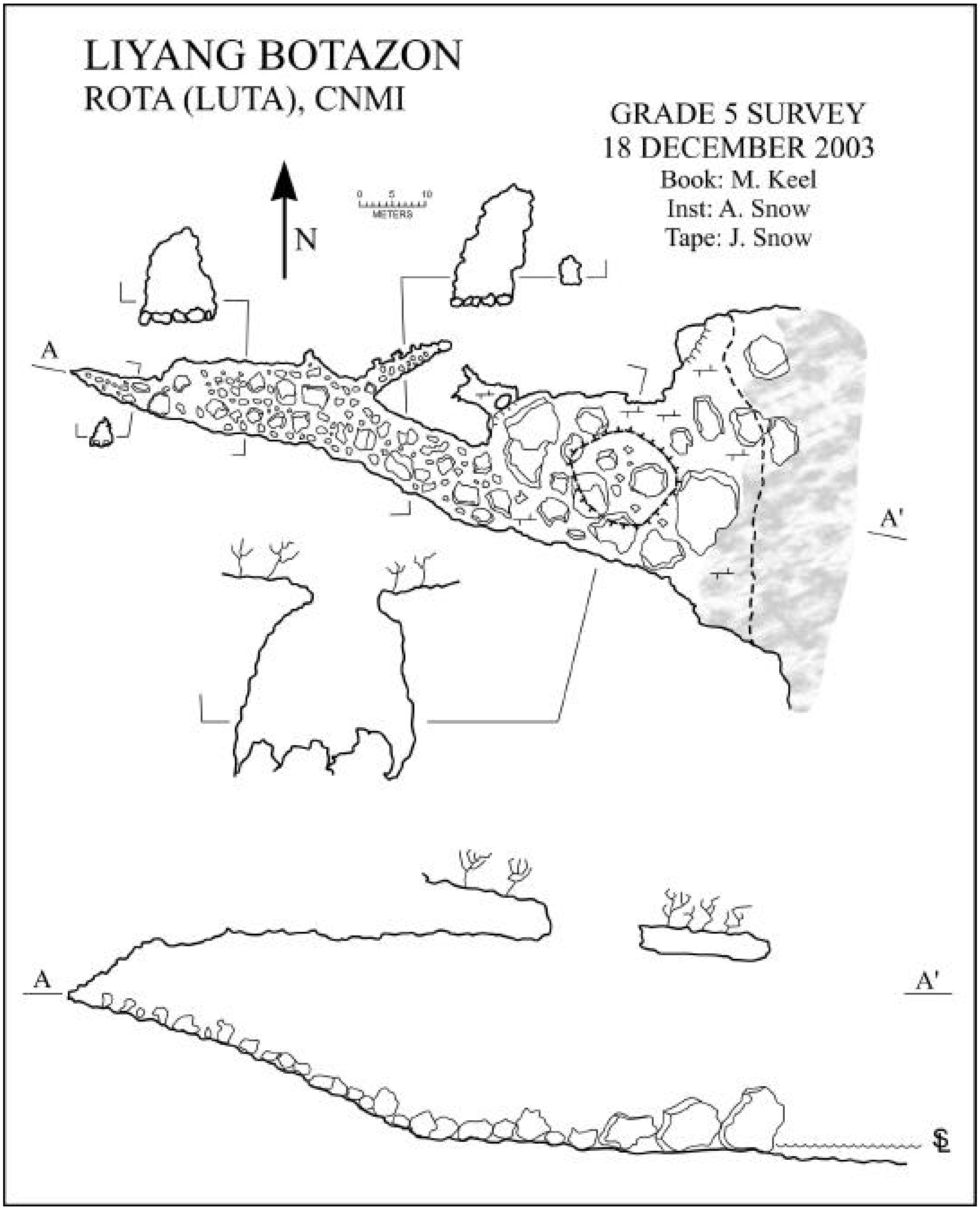

Figure 259: Map of Liyang Botazon

Liyang Finta

Liyang Finta is located at about 50 m elevation, just below the cliff top, at the head of a notch in the cliff between *Taksunok* and *I Koridot*. The fracture that *Liyang Finta* is obviously developed along is expressed in the cliff top above the cave. The entrance to *Liyang Finta* is dominated by several large boulders. For about 4 m beyond these boulders, the cave floor slopes gently downward, while the ceiling rises to about 6 m. The ceiling has a skylight in the fracture along which the cave is developed. At the rear of the main room is a large pile of boulders. To the southeast of the main room, there is a room about 3 m high floored with loose cobbles and soil.

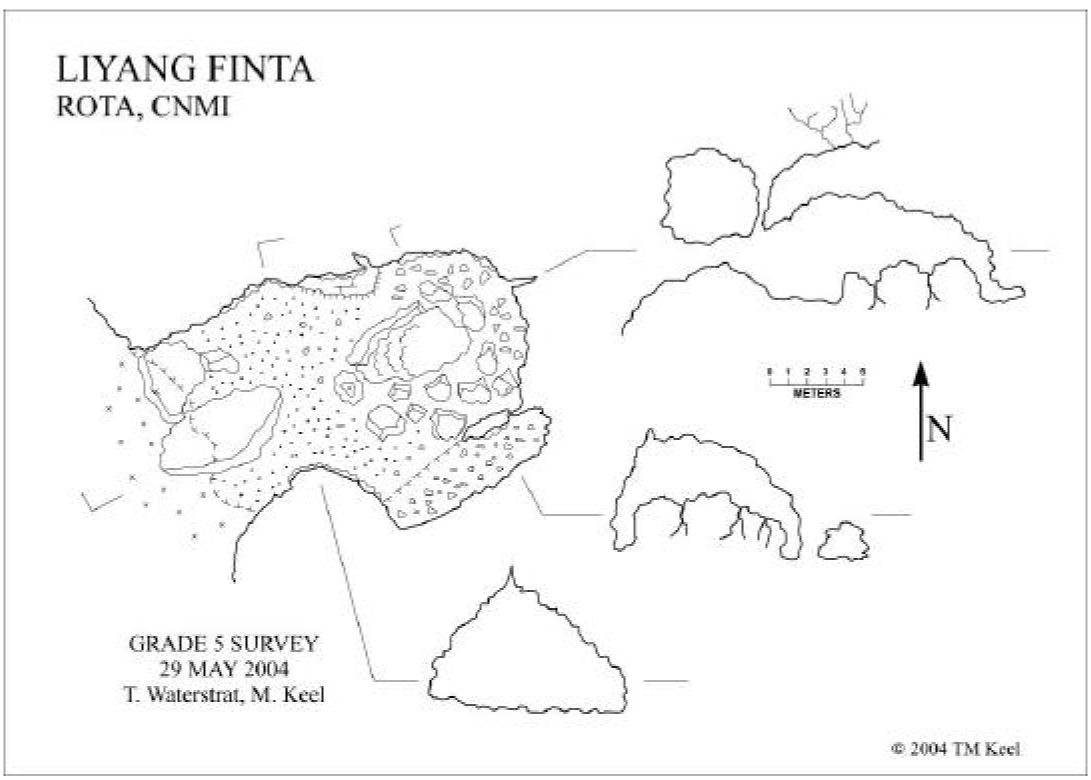

Figure 260: Map of Liyang Finta

Liyang Lu'ao

Liyang Lu'ao is one of several linear caves located in the cliff base, north of the *Chenchon* Bird Sanctuary overlook. *Liyang Lu'ao* is located about 40 m south of *Liyang Paluma*, which is the cave immediately at the bottom of the climb down from the cliff top. *Liyang Lu'ao* has an enormous, dramatic entrance, especially when seen from the large boulder pile that has accumulated at the entrance from breakdown. No evidence of recent breakdown was seen. From the top of the breakdown pile, the entrance is about 8 m high. Just inside the drip line, off the boulder pile, the ceiling is about 12 – 15 m high for about 30 m where it drops to 10–11 m for the rest of the cave. *Liyang Lu'ao* is about 14 m wide at the drip line, gradually narrowing to about 4 m at about 35 m. Beyond about 35 m, *Liyang Lu'ao* gradually widens to about 9 m before narrowing at the rear. *Liyang Lu'ao* extends a total of about 65 m from the drip line. The floor of the cave beyond the breakdown pile at the entrance in mainly soil and guano with a few cobble. Along the left wall, mid-way back in the cave are two pieces of a breakdown slab the are each about 8 m high, 2-3 m thick. The first is about 10 m long and the second is about 8 m long. These slabs are standing nearly vertical and appear to have fallen as one piece. Just toward the drip line from the outer slab is a sloping bed rock shelf on the south wall that leads up to a small passage that ends at about 3 m. *Liyang Lu'ao* is developed along a fracture that is prominent in the ceiling of the cave for its full length.

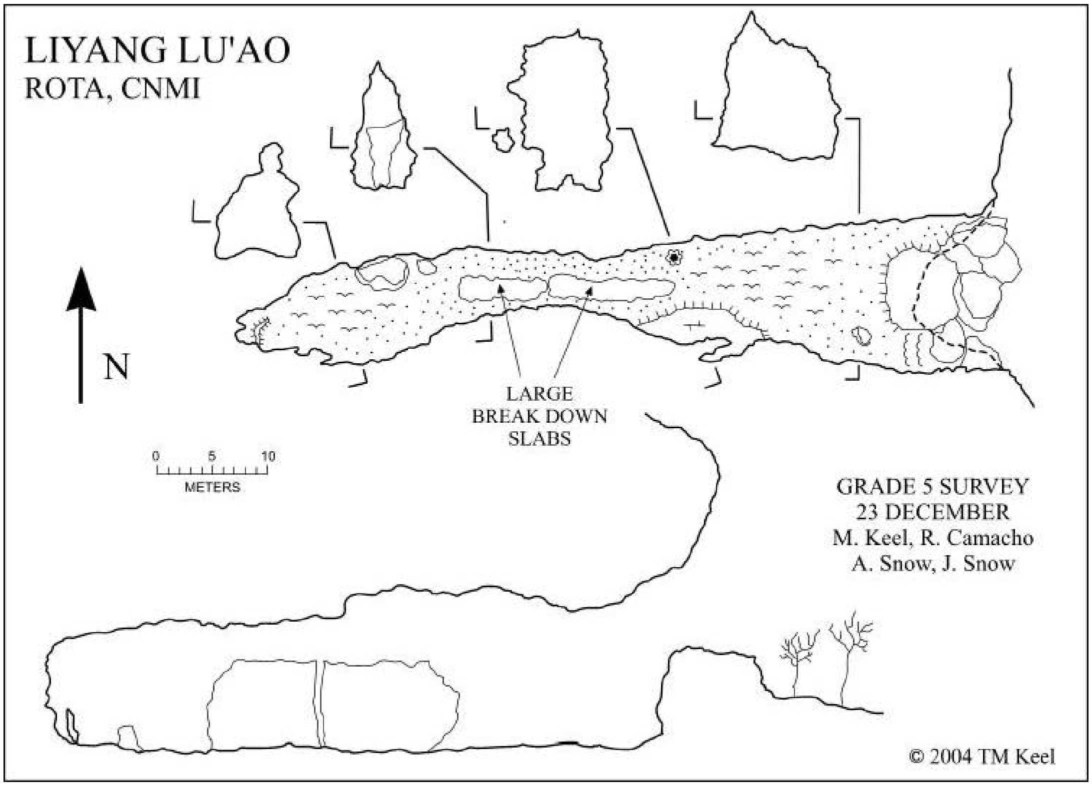

Figure 261: Map of Liyang Lu’ao

Liyang Matan

Liyang Matan is the southern most of the three large cave entrances at *Puntan Fina Atkos* near *As Matmos*, at about 30 m elevation. The area just outside the entrance is dominated by massive breakdown block the has dimensions of 10+ m. The entrance is very large; about 20 m high and 30 m wide. The drip line forms a deep "V" into one of the fractures that the cave is developed along. About 1 m in from the point of the "V" is an oblong skylight that lends the cave its name: *Liyang Matan* (Eye Cave). The floor of the entrance room is decorated with highly weathered speleothems while the ceiling has phototropic stalactites. The cave continues as a wide, tall room for about 40 m from the "eye" before the size changes abruptly. At the left rear is a very short passage (1-2 m) that is in alignment with one of the fractures seen in the ceiling of the main room. At the right rear, a short climb down leads to a narrow canyon that can be followed for about 50 m, sometimes requiring crawling. Inaccessible higher levels can be seen from below. This narrow passage is in alignment with one of the fractures visible in the ceiling of the main room.

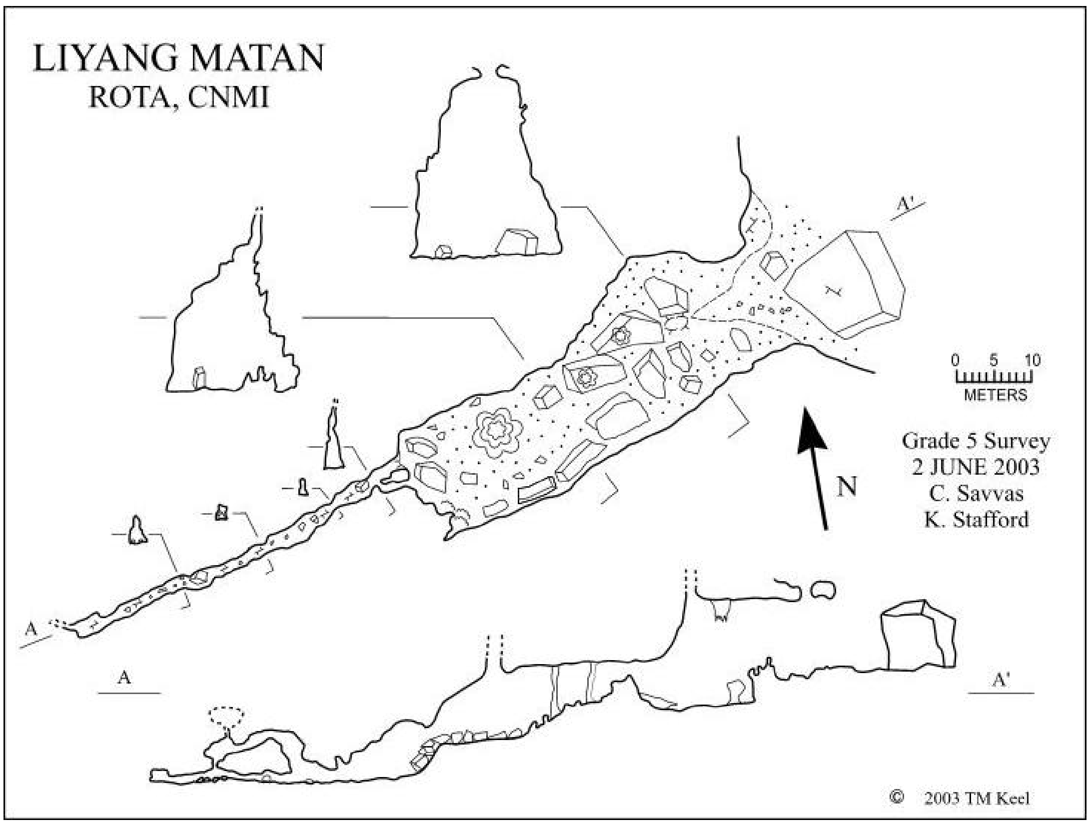

Figure 262: Map of Liyang Matan

Liyang Neni

Liyang Neni is one of several linear caves located in the cliff base, north of the *Chenchon* Bird Sanctuary overlook. *Liyang Neni* is located about 30 m southwest of the much larger Arrowhead Cave. Like the other caves in the area, *Liyang Neni* is developed along an obvious fracture, but reaches only about 18 m back from the drip line. The ceiling is 7-8 m for the length of the cave and tapers into the fracture. About 3 m back from the drip line there is a skylight about 1 m across. *Liyang Neni* is about 8 m wide at the drip line, including alcoves on the left and right. The cave quickly narrows to about 3 m wide and gradually narrows to the back. The floor of the cave is primarily soil with a few cobbles and boulders.

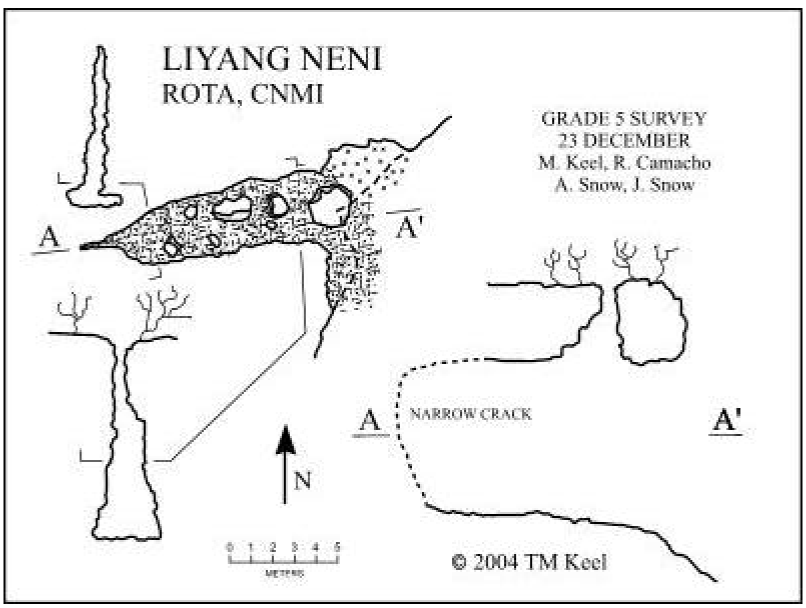

Figure 263: Map of Liyang Neni

Liyang Paluma

Liyang Paluma is the northernmost of several linear caves located in the cliff base, north of the *Chenchon* Bird Sanctuary overlook. *Liyang Paluma* is about 37 m long, about 7 m wide at the drip line and about 3 m wide for most of its length, before narrowing significantly at the back. The floor of *Liyang Paluma* is covered with soil (possibly guano) and has some boulders and cobbles near the entrance. The entrance dominated by a 3 m high breakdown block that spans the passage. The ceiling of *Liyang Paluma* clearly expresses the fracture along which the cave is developed. In several places the actual ceiling height could not be measured from the floor because of high pockets developed along the fracture. The appears to be no safe way to reach these parts of the cave from below. None of the pockets appeared to reach the surface.

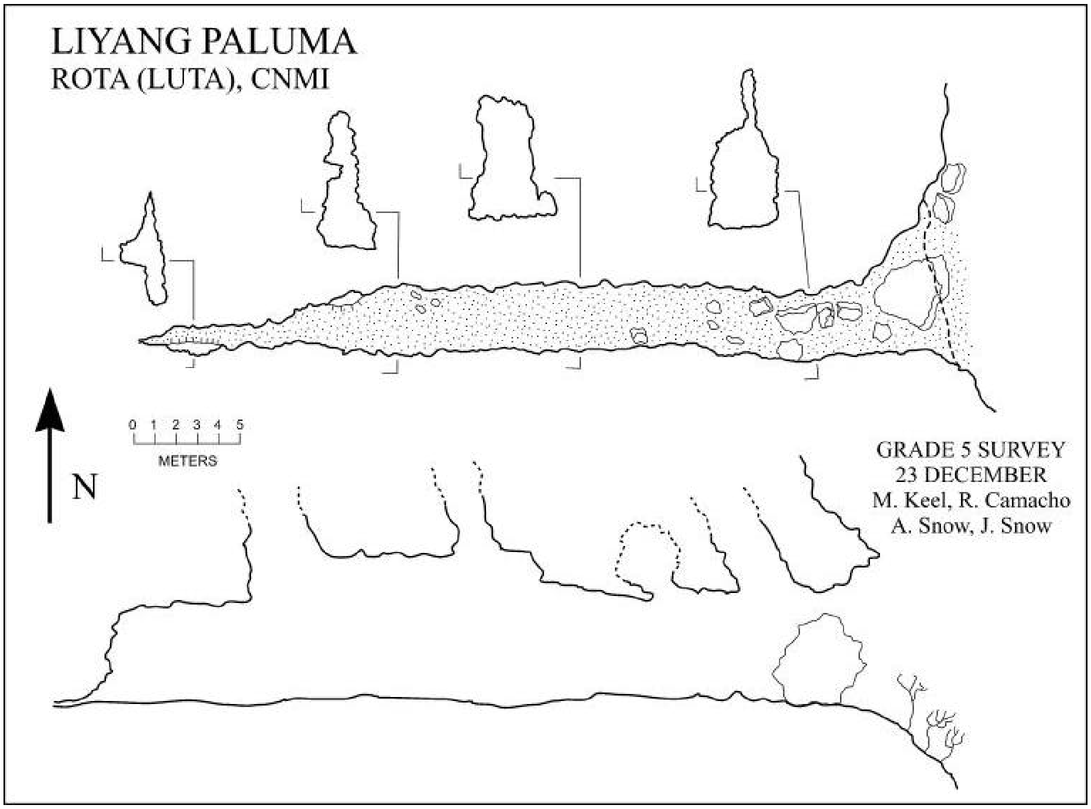

Figure 264: Map of Liyang Paluma

Liyang Siete

Liyang Siete is the southernmost of several linear caves located in the cliff face, north of the *Chenchon* Bird Sanctuary overlook, at about 30 m elevation. *Liyang Siete* is difficult to classify due to its fragmentary, remnant nature. It may be what is left of a mixing zone fracture cave that was once similar to the others in the area, although it would have been much higher than the others. It may be the result of solutional modification of a bank margin failure block. Gaining access to this feature from the cliff top might allow observations that would help in understanding its origin.

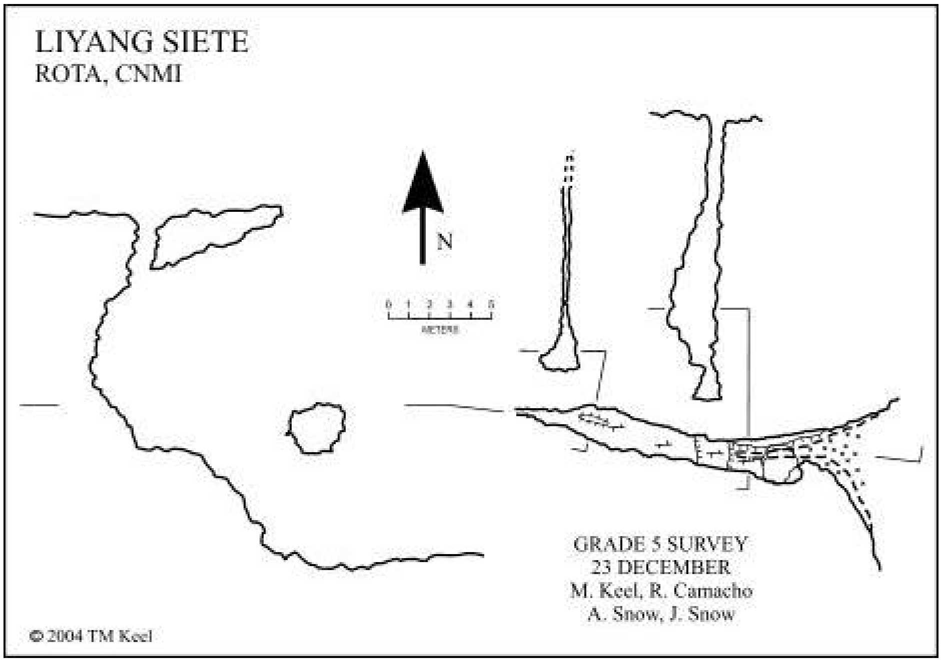

Figure 265: Map of Liyang Siete

Pictograph Cave

Pictograph cave is well known on the island but apparently seldom visited despite a trail leading to it. It is located at about 130 m elevation, about 200 m down hill from the old Japanese railroad bed on *Gampapa* ridge. The entrance to the cave is in a "canyon" that is apparently the un-roofed outer part of the cave. At the drip line, the entrance is about 5 m wide and about 5 m high. Man-made steps lead down to the main floor level of the cave, where the ceiling is about 7 m high, and the walls 4-6 m apart. The cave consists of one linear passage, about 60 m long, apparently developed along the fracture that is visible in the ceiling. About 30 m back the cave widens to about 12 m before narrowing to end in an area decorated with speleothems. The walls are decorated in several places with pictographs. The cave contains extensive evidence use in modern times. The nature of many of the artifacts indicates that the cave was used during the Japanese era.

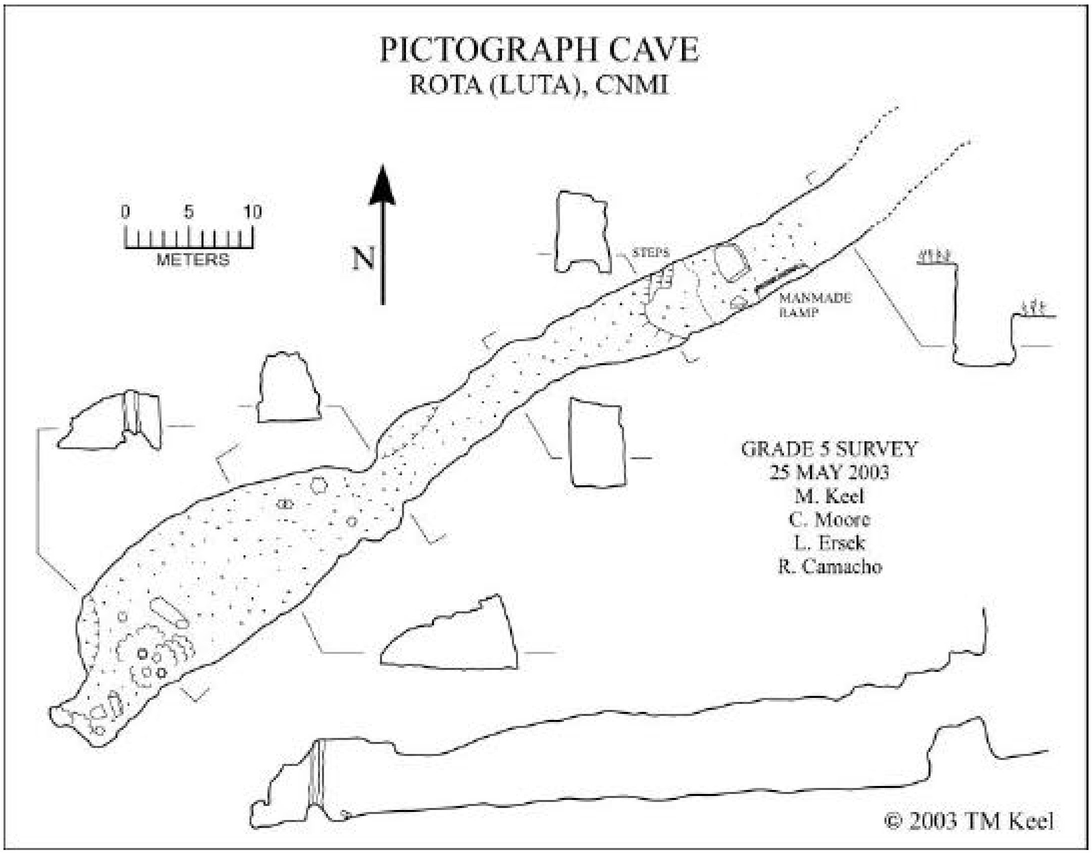

Figure 266: Map of Pictograph Cave

Pit Caves

Truck Rig Pit

Truck Rig Pit is located adjacent to the parking area or Pictograph Cave at *Gampapa.* The entrance to the pit is about 1X1 m. Truck Rig Pit is developed along a fracture that strikes about 60°, the same general strike as Pictograph Cave. The pit reaches a maximum depth of about 9 m, and is 1-2 m wide. The fracture along which Truck Rig Pit is developed can be seen to continue laterally and vertically.

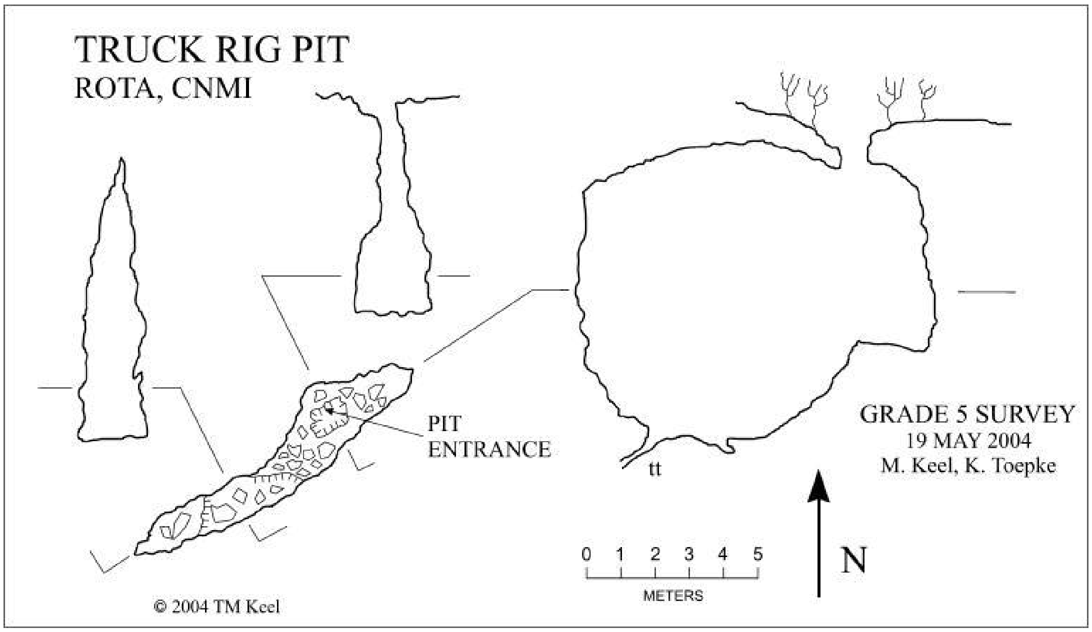

Figure 267: Map of Truck Rig Pit

TAIPINGOT

Mixing-Zone Fracture Cave

Bee Cave

Bee Cave is located on the northwest side of the Wedding Cake (*Taipingot*) about 150 m from Tewksbury Park and is accessible by climbing about 9 m up the cliff face. Bee Cave is a shallow overhang developed along a fracture in the limestone bedrock. There is a beehive hanging over the entrance to this small feature.

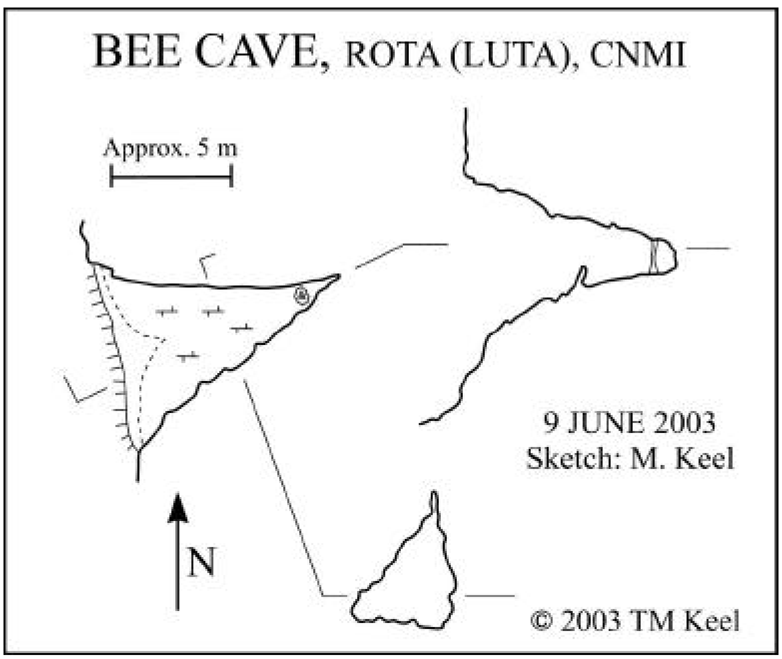

Figure 268: Map of Bee Cave

Flank Margin Cave

Broken Mortar Cave

Broken Mortar Cave is located at *Liyo* on the *Taipingot* (Wedding Cake) at about 100 m elevation. Broken Mortar Cave is an overhang about 12 m long east-west and 4-5 m wide. It appears to be a remnant of a larger cave and also contains some bedrock mortars, one of which is broken in half.

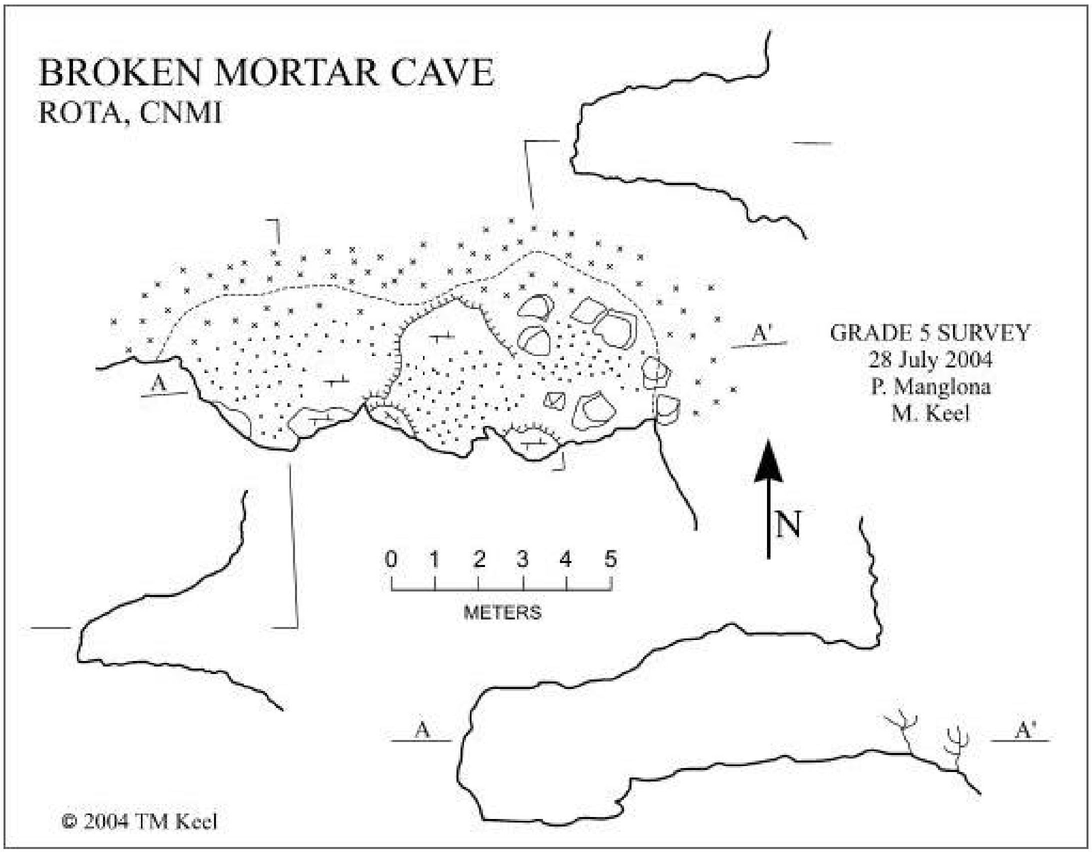

Figure 269: Map of Broken Mortar Cave

Sea Cave

Paupau Sea Cave

Paupau Sea Cave is located near *Songsong* Village, on the coast, about 250 m south of the old Rota *Paupau* Hotel at about 1 m elevation. The cave is about 11 m long, about 4 m wide with a simple oval cross section. The floor is mostly bedrock with a few loose boulders and cobbles.

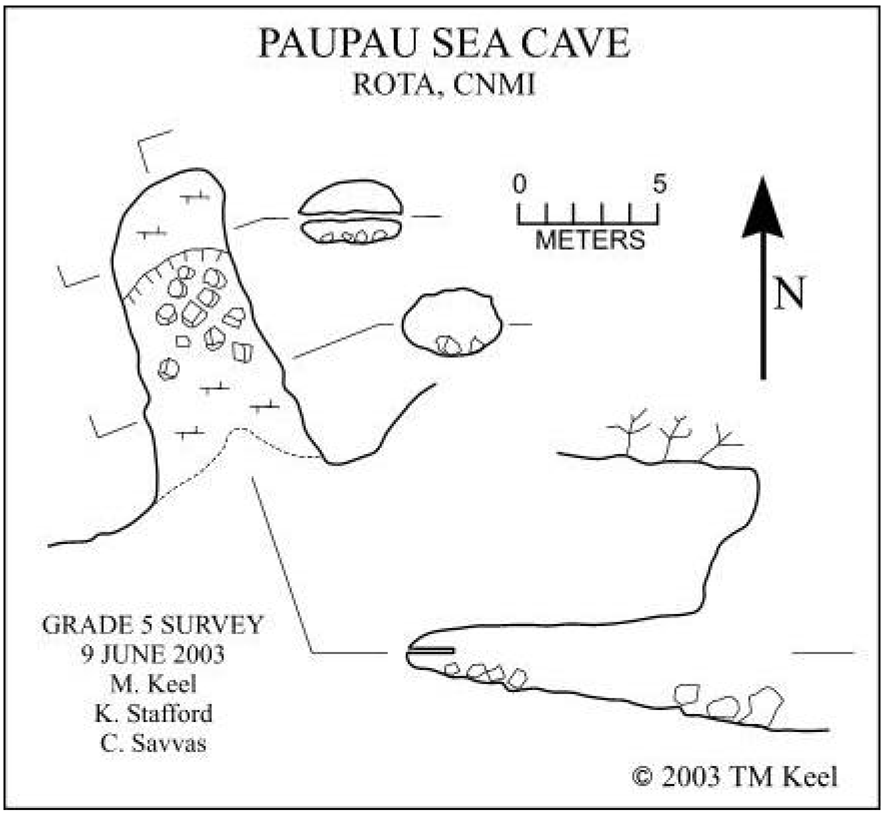

Figure 270: Map of Paupau Sea Cave

APPENDIX D

CAVE AND KARST INVENTORY OF SAIPAN

MAPS AND DESCRIPTIONS

The following data is used with permission from Mylroie (personal communication). The data has been reorganized from its original alphabetical order to being organized alphabetically by province and karst feature type. Table 23 shows the caves of Saipan in alphabetical order, Table 24 shows the caves of Saipan alphabetically within cave type, and Table 25 shows them alphabetically within the province. For ease of use, all tables include the page number that the cave's map and description starts.

Table 23: Table of the caves of Saipan in alphabetical order

Cave Name	Cave Type	Province	Page Number
Hourglass Cave	Unknown Origin	Unknown	504
I Madog (The Grotto)	Sea Cave	Low Platform and Terraces	505
Kalabera Cave	Discharge	Low Platform and Terraces	503
Ladder Beach Caves	Flank Margin Cave	Low Platform and Terraces	507

Table 24: The caves of Saipan alphabetically by cave type

Cave Name	Cave Type	Province	Page Number
Kalabera Cave	Discharge	Low Platform and Terraces	503
Ladder Beach Caves	Flank Margin Cave	Low Platform and Terraces	507
I Madog (The Grotto)	Sea Cave	Low Platform and Terraces	505
Hourglass Cave	Unknown Origin	Unknown	504

Table 25: The caves of Saipan alphabetically by province

Cave Name	Cave Type	Province	Page Number
I Madog (The Grotto)	Sea Cave	Low Platform and Terraces	505
Kalabera Cave	Discharge	Low Platform and Terraces	503
Ladder Beach Caves	Flank Margin Cave	Low Platform and Terraces	507
Hourglass Cave	Unknown Origin	Unknown	504

Discharge Features

Kalabera Cave

There was no description provided for this discharge feature.

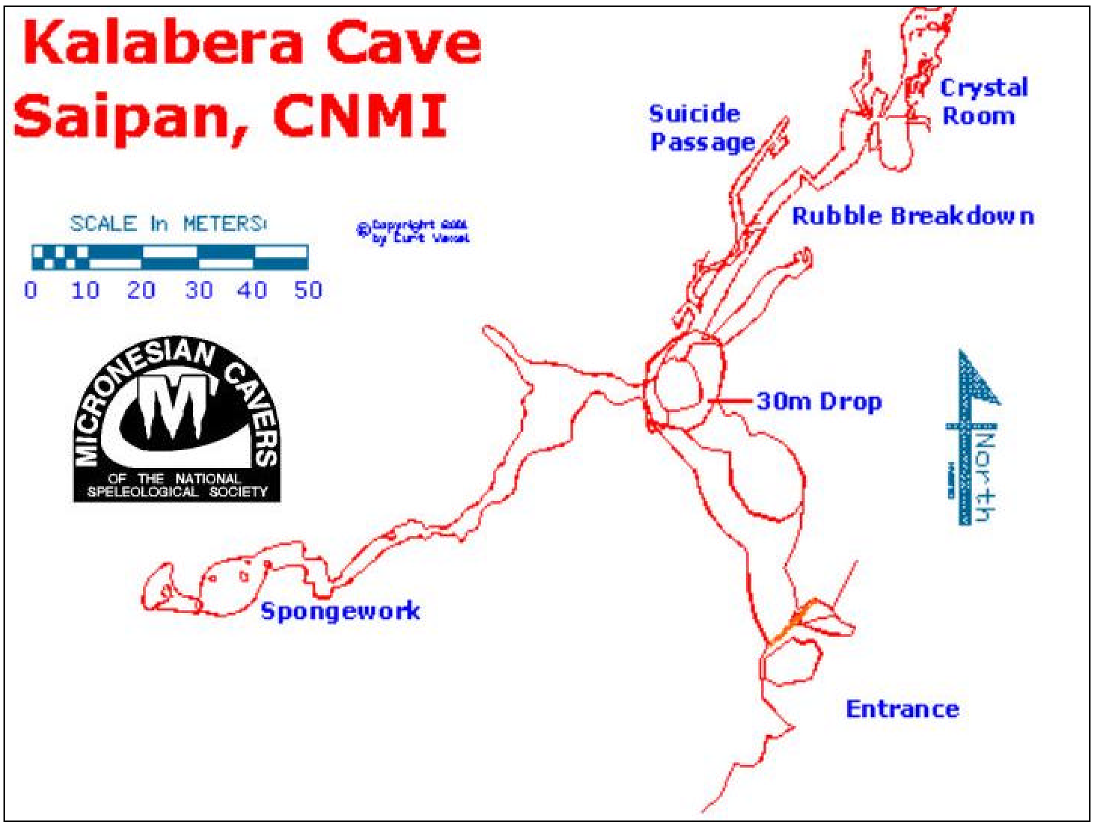

Figure 271: Plan map of Kalabera Cave

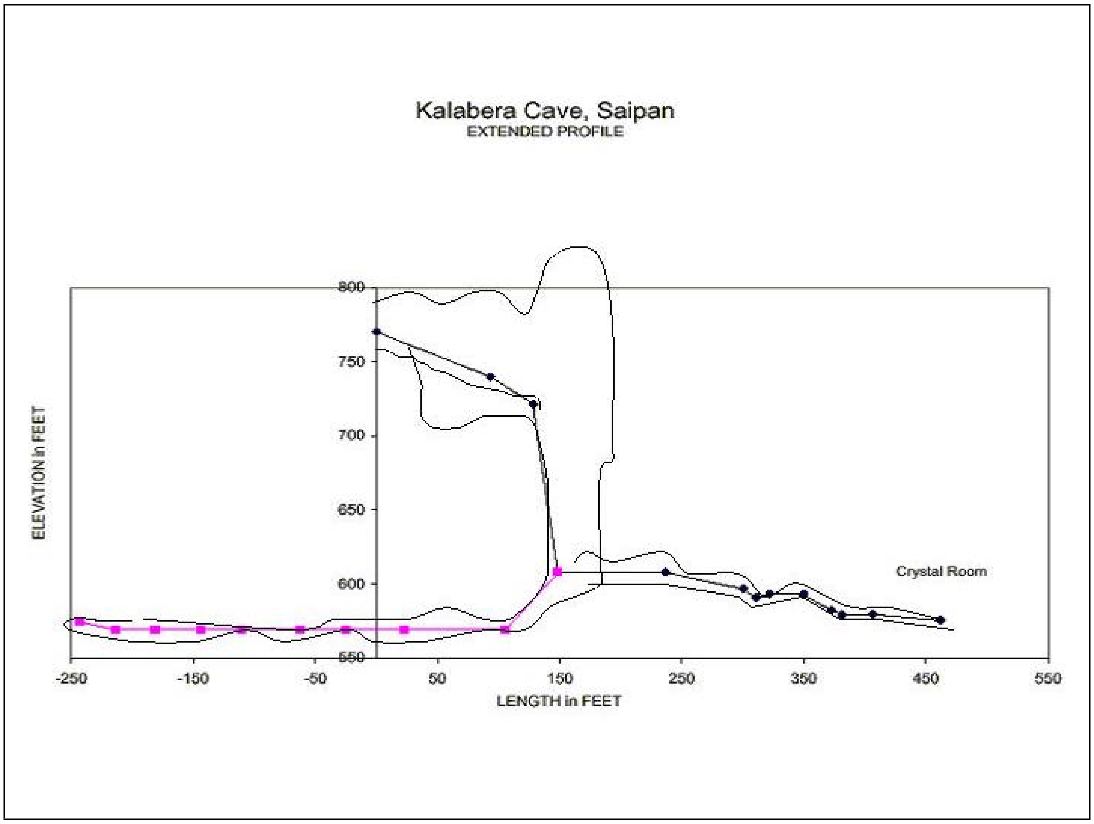

Figure 272: Profile map of Kalabera Cave

Caves of Unknown Origin

Hourglass Cave

There was no description provided for this cave of unknown origin.

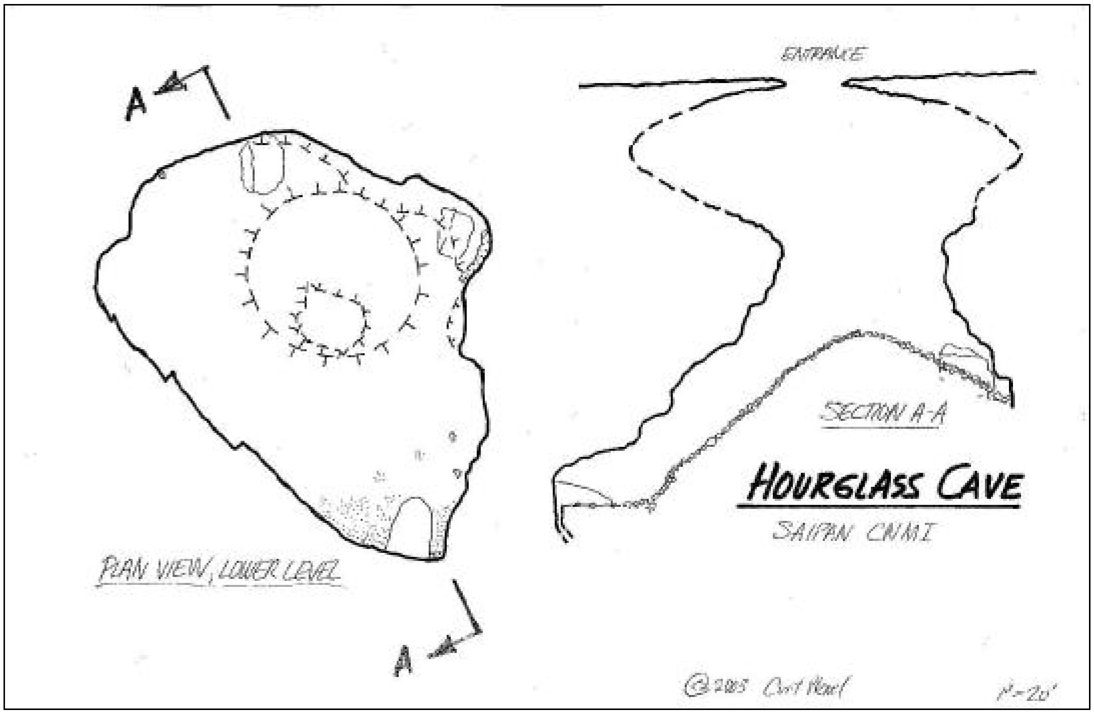

Figure 273: Map of Hourglass Cave

Sea Caves

I Madog Cave

There was no description provided for this sea cave.

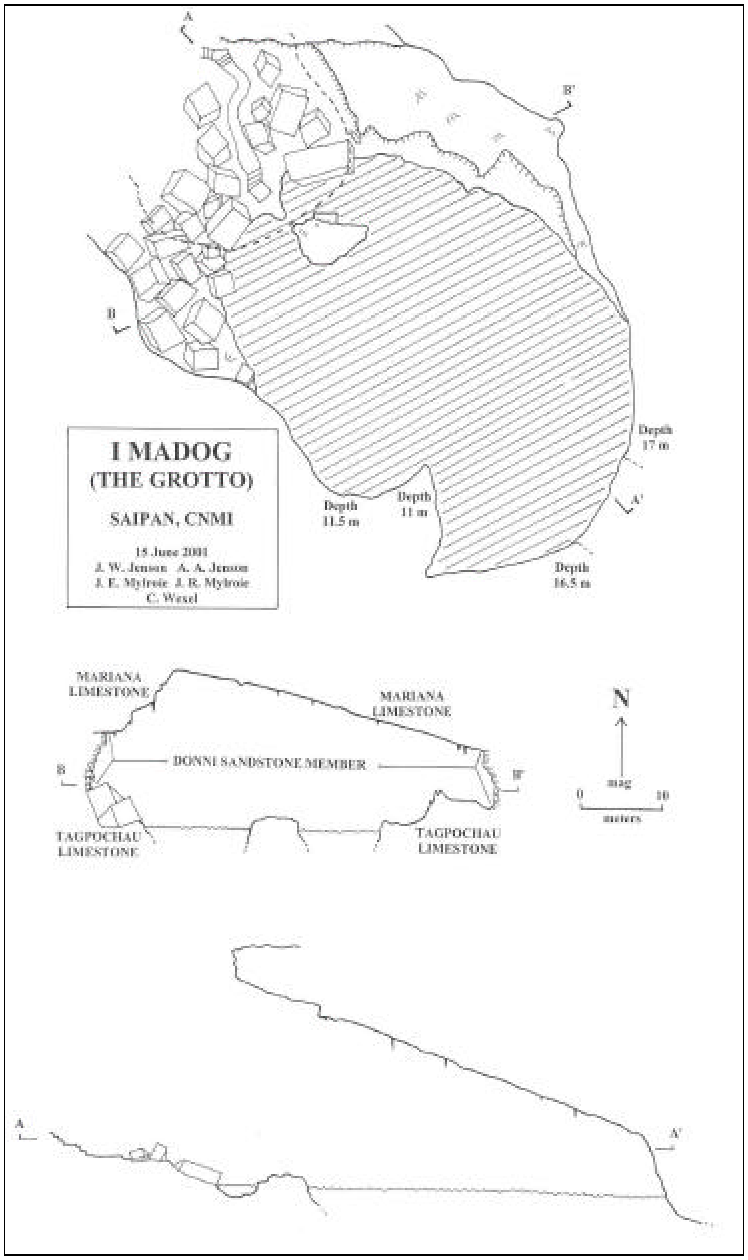

Figure 274: Map of I Madog (The Grotto)

Flank Margin Caves

Ladder Beach Cave

There was no description provided for this flank margin cave.

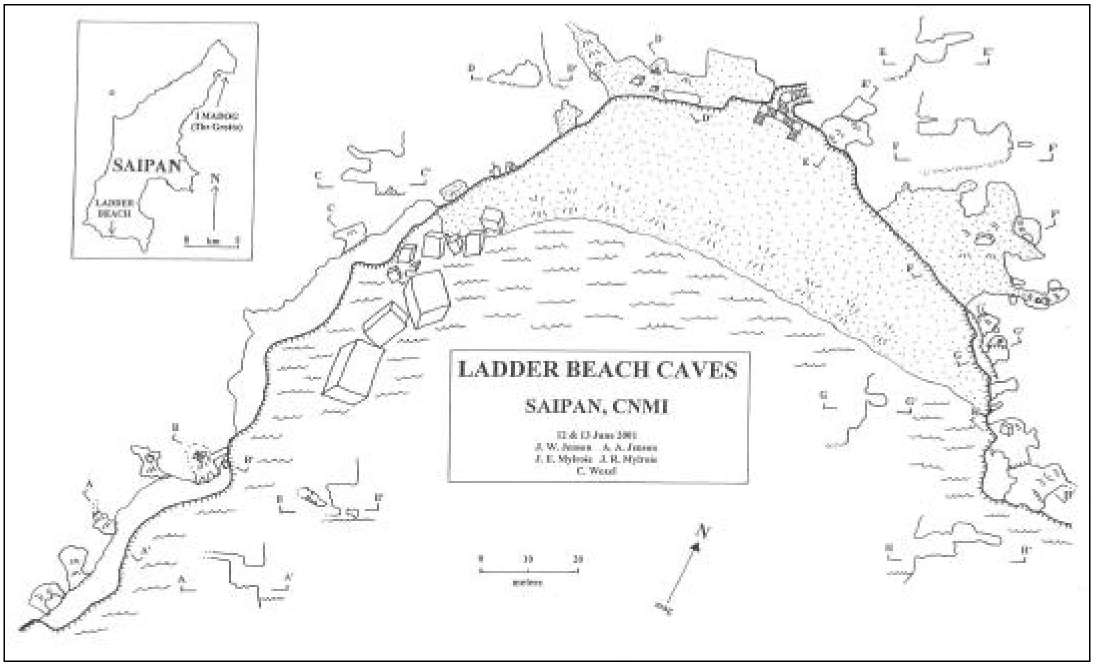

Figure 275: Map of Ladder Beach Caves

APPENDIX E

CAVE AND KARST INVENTORY OF TINIAN

MAPS AND DESCRIPTIONS

The following data is used with permission from Stafford (2003). The data has been reorganized from its original alphabetical order to being organized alphabetically by province and karst feature type. The only changes made were minor spelling and grammatical corrections. Table 26 shows the caves of Tinian in alphabetical order, Table 27 shows the caves of Tinian alphabetically within cave type, and Table 28 shows them alphabetically within the province. For ease of use, all tables include the page number that the cave's map and description starts.

Table 26: The caves of Tinian alphabetically by cave name

Cave Name	Cave Type	Province	Page Number
"600 M" Fracture Caves	Mixing-Zone Fracture Cave	Southeastern Ridge	636
Andyland Cave	Flank Margin Cave	Median Valley	561
Barcinas East Cave	Flank Margin Cave	Median Valley	562
Barcinas West Cave	Flank Margin Cave	Median Valley	563
Barely Cave	Flank Margin Cave	Central Plateau	523
Bee Hooch Cave	Flank Margin Cave	Southeastern Ridge	602
Body Rapel Cave	Flank Margin Cave	Southeastern Ridge	605
Broken Stal Cave	Flank Margin Cave	Southeastern Ridge	606
Cannon Cave	Flank Margin Cave	Central Plateau	525
Carolina's Fracture Cave	Fissure Cave	Southeastern Ridge	595
Cave Without a Cave	Flank Margin Cave	Southeastern Ridge	608
Cave Without a Roof	Flank Margin Cave	Southeastern Ridge	608
Cavelet Cave	Flank Margin Cave	Central Plateau	526
Central Mendiola Cave Complex	Flank Margin Cave	Central Plateau	527
Cetacean Cave	Discharge Feature	Southeastern Ridge	595
Chiget Fracture	Fissure Cave	Central Plateau	520
Cobble Cave	Flank Margin Cave	Central Plateau	530
Coconut Trap Cave	Flank Margin Cave	Southeastern Ridge	609
Command Post Cave	Flank Margin Cave	North-Central Highland	586
Cowrie Cave	Flank Margin Cave	Central Plateau	531
CUC Cave	Banana Hole	Median Valley	555
Danko's Misery	Fissure Cave	Southeastern Ridge	596

Table 26 (Continued)

Cave Name	Cave Type	Province	Page Number
Death Fracture	Fissure Cave	Central Plateau	521
Dos Cenotes Cave	Flank Margin Cave	Central Plateau	532
Dos Sakis Cave Complex	Flank Margin Cave	Central Plateau	533
Dripping Tree Fracture Cave	Fissure Cave	Median Valley	558
Dump Coke Cave	Flank Margin Cave	Central Plateau	534
Dynasty Cave	Flank Margin Cave	Median Valley	564
East Suicide Cliff Cave	Flank Margin Cave	Southeastern Ridge	610
Edwin's Ranch Cave	Flank Margin Cave	Central Plateau	536
Elevator Cave	Flank Margin Cave	Southeastern Ridge	611
False Floor Cave	Flank Margin Cave	Southeastern Ridge	612
Five Bee Cave Complex	Flank Margin Cave	Southeastern Ridge	613
Flamingo Tail Caves	Flank Margin Cave	Central Plateau	537
Fleming Point Cave	Flank Margin Cave	Central Plateau	538
Full Bottle Cave	Fissure Cave	Southeastern Ridge	597
Gecko Cave	Discharge Feature	Median Valley	556
Half Dozen Cave	Flank Margin Cave	Central Plateau	540
Headless Tourist Pit	Pit Cave	Southeastern Ridge	639
Hermit Crab Cave	Flank Margin Cave	Southeastern Ridge	614
Hidden Beach Cave	Flank Margin Cave	Median Valley	565
Johns Small Cave	Flank Margin Cave	Median Valley	567
Lasu Recharge Cave	Recharge Cave	North-Central Highland	589
Leprosy Cave	Flank Margin Cave	Median Valley	568
Leprosy Discharge Feature	Discharge Feature	Median Valley	557
Liyang Barangka	Flank Margin Cave	Southeastern Ridge	615
Liyang Dangkolo	Flank Margin Cave	Median Valley	569
Liyang Diapblo	Flank Margin Cave	Central Plateau	541
Liyang Gntot	Flank Margin Cave	North-Central Highland	587
Liyang Mohlang	Flank Margin Cave	Southeastern Ridge	617
Liyang Popporput	Fissure Cave	Southeastern Ridge	599
Liyang Sampapa	Discharge Feature	Central Plateau	519
Liyang Umumu	Banana Hole	Central Plateau	518
Lower Suicide Cliff Cave Complex	Flank Margin Cave	Southeastern Ridge	618
Masalok Fracture Cave Complex	Fissure Cave	Southeastern Ridge	600
Mendiola Arch Cave Complex	Flank Margin Cave	Central Plateau	542
Metal Door Cave	Flank Margin Cave	North-Central Highland	588
Metal Spike Cave	Flank Margin Cave	Median Valley	571
Metal Strecher Cave	Flank Margin Cave	Southeastern Ridge	621

Table 26 (Continued)

Cave Name	Cave Type	Province	Page Number
Modified Cave	Flank Margin Cave	Southeastern Ridge	622
Monica Wants to be Like Kevin Cave	Flank Margin Cave	Central Plateau	544
North Unai Dangkolo	Flank Margin Cave	Median Valley	575
Northern Playground Cave	Flank Margin Cave	Southeastern Ridge	623
Nuestra Senora Complex	Flank Margin Cave	Central Plateau	545
Orange Cave	Flank Margin Cave	Central Plateau	548
Pebble Cave	Flank Margin Cave	Central Plateau	548
Pina Cave Complex	Flank Margin Cave	Southeastern Ridge	624
Playground Cave	Flank Margin Cave	Southeastern Ridge	626
Plunder Cave	Mixing-Zone Fracture Cave	Median Valley	581
Radio Inactive Cave	Flank Margin Cave	Southeastern Ridge	627
Red Snapper Cave	Flank Margin Cave	Central Plateau	549
Rock Hammer Cave	Flank Margin Cave	Central Plateau	550
Rogue Cave	Discharge Feature	Northern Lowland	591
Rootcicle Cave	Banana Hole	North-Central Highland	585
Skip Jack Cave	Flank Margin Cave	Southeastern Ridge	628
Skull Cave Complex	Flank Margin Cave	Southeastern Ridge	630
Skylight Cave	Flank Margin Cave	Southeastern Ridge	631
Solitary Cave	Flank Margin Cave	Southeastern Ridge	633
South Mendiola Cave	Flank Margin Cave	Central Plateau	552
South Unai Dangkolo	Flank Margin Cave	Median Valley	577
Swimming Hole Complex	Flank Margin Cave	Median Valley	578
Twin Ascent Caves	Flank Margin Cave	Southeastern Ridge	633
Unai Chiget	Mixing-Zone Fracture Cave	Northern Lowland	593
Unai Lamlam	Flank Margin Cave	Northern Lowland	592
Unai Masalok	Flank Margin Cave	Median Valley	579
Water Cave	Mixing-Zone Fracture Cave	Median Valley	583
West Lasu Depression Cave	Recharge Cave	Central Plateau	553
West Suicide Cliff Caves	Flank Margin Cave	Southeastern Ridge	634

Table 27: The caves of Tinian alphabetically by cave type

Cave Name	Cave Type	Province	Page Number
CUC Cave	Banana Hole	Median Valley	555
Liyang Umumu	Banana Hole	Central Plateau	518
Rootcicle Cave	Banana Hole	North-Central Highland	585
Cetacean Cave	Discharge Feature	Southeastern Ridge	595
Gecko Cave	Discharge Feature	Median Valley	556
Leprosy Discharge Feature	Discharge Feature	Median Valley	557
Liyang Sampapa	Discharge Feature	Central Plateau	519
Rogue Cave	Discharge Feature	Northern Lowland	591
Carolina's Fracture Cave	Fissure Cave	Southeastern Ridge	595
Chiget Fracture	Fissure Cave	Central Plateau	520
Danko's Misery	Fissure Cave	Southeastern Ridge	596
Death Fracture	Fissure Cave	Central Plateau	521
Dripping Tree Fracture Cave	Fissure Cave	Median Valley	558
Full Bottle Cave	Fissure Cave	Southeastern Ridge	597
Liyang Popporput	Fissure Cave	Southeastern Ridge	599
Masalok Fracture Cave Complex	Fissure Cave	Southeastern Ridge	600
Andyland Cave	Flank Margin Cave	Median Valley	561
Barcinas East Cave	Flank Margin Cave	Median Valley	562
Barcinas West Cave	Flank Margin Cave	Median Valley	563
Barely Cave	Flank Margin Cave	Central Plateau	523
Bee Hooch Cave	Flank Margin Cave	Southeastern Ridge	602
Body Rapel Cave	Flank Margin Cave	Southeastern Ridge	605
Broken Stal Cave	Flank Margin Cave	Southeastern Ridge	606
Cannon Cave	Flank Margin Cave	Central Plateau	525
Cave Without a Cave	Flank Margin Cave	Southeastern Ridge	608
Cave Without a Roof	Flank Margin Cave	Southeastern Ridge	608
Cavelet Cave	Flank Margin Cave	Central Plateau	526
Central Mendiola Cave Complex	Flank Margin Cave	Central Plateau	527
Cobble Cave	Flank Margin Cave	Central Plateau	530
Coconut Trap Cave	Flank Margin Cave	Southeastern Ridge	609
Command Post Cave	Flank Margin Cave	North-Central Highland	586
Cowrie Cave	Flank Margin Cave	Central Plateau	531
Dos Cenotes Cave	Flank Margin Cave	Central Plateau	532
Dos Sakis Cave Complex	Flank Margin Cave	Central Plateau	533
Dump Coke Cave	Flank Margin Cave	Central Plateau	534
Dynasty Cave	Flank Margin Cave	Median Valley	564
East Suicide Cliff Cave	Flank Margin Cave	Southeastern Ridge	610

Table 27 (Continued)

Cave Name	Cave Type	Province	Page Number
Edwin's Ranch Cave	Flank Margin Cave	Central Plateau	536
Elevator Cave	Flank Margin Cave	Southeastern Ridge	611
False Floor Cave	Flank Margin Cave	Southeastern Ridge	612
Five Bee Cave Complex	Flank Margin Cave	Southeastern Ridge	613
Flamingo Tail Caves	Flank Margin Cave	Central Plateau	537
Fleming Point Cave	Flank Margin Cave	Central Plateau	538
Half Dozen Cave	Flank Margin Cave	Central Plateau	540
Hermit Crab Cave	Flank Margin Cave	Southeastern Ridge	614
Hidden Beach Cave	Flank Margin Cave	Median Valley	565
Johns Small Cave	Flank Margin Cave	Median Valley	567
Leprosy Cave	Flank Margin Cave	Median Valley	568
Liyang Barangka	Flank Margin Cave	Southeastern Ridge	615
Liyang Dangkolo	Flank Margin Cave	Median Valley	569
Liyang Diapblo	Flank Margin Cave	Central Plateau	541
Liyang Gntot	Flank Margin Cave	North-Central Highland	587
Liyang Mohlang	Flank Margin Cave	Southeastern Ridge	617
Lower Suicide Cliff Cave Complex	Flank Margin Cave	Southeastern Ridge	618
Mendiola Arch Cave Complex	Flank Margin Cave	Central Plateau	542
Metal Door Cave	Flank Margin Cave	North-Central Highland	588
Metal Spike Cave	Flank Margin Cave	Median Valley	571
Metal Strecher Cave	Flank Margin Cave	Southeastern Ridge	621
Modified Cave	Flank Margin Cave	Southeastern Ridge	622
Monica Wants to be Like Kevin Cave	Flank Margin Cave	Central Plateau	544
North Unai Dangkolo	Flank Margin Cave	Median Valley	575
Northern Playground Cave	Flank Margin Cave	Southeastern Ridge	623
Nuestra Senora Complex	Flank Margin Cave	Central Plateau	545
Orange Cave	Flank Margin Cave	Central Plateau	548
Pebble Cave	Flank Margin Cave	Central Plateau	548
Pina Cave Complex	Flank Margin Cave	Southeastern Ridge	624
Playground Cave	Flank Margin Cave	Southeastern Ridge	626
Radio Inactive Cave	Flank Margin Cave	Southeastern Ridge	627
Red Snapper Cave	Flank Margin Cave	Central Plateau	549
Rock Hammer Cave	Flank Margin Cave	Central Plateau	550
Skip Jack Cave	Flank Margin Cave	Southeastern Ridge	628
Skull Cave Complex	Flank Margin Cave	Southeastern Ridge	630
Skylight Cave	Flank Margin Cave	Southeastern Ridge	631
Solitary Cave	Flank Margin Cave	Southeastern Ridge	633

Table 27 (Continued)

Cave Name	Cave Type	Province	Page Number
South Mendiola Cave	Flank Margin Cave	Central Plateau	552
South Unai Dangkolo	Flank Margin Cave	Median Valley	577
Swimming Hole Complex	Flank Margin Cave	Median Valley	578
Twin Ascent Caves	Flank Margin Cave	Southeastern Ridge	633
Unai Lamlam	Flank Margin Cave	Northern Lowland	592
Unai Masalok	Flank Margin Cave	Median Valley	579
West Suicide Cliff Caves	Flank Margin Cave	Southeastern Ridge	634
"600 M" Fracture Caves	Mixing-Zone Fracture Cave	Southeastern Ridge	636
Plunder Cave	Mixing-Zone Fracture Cave	Median Valley	581
Unai Chiget	Mixing-Zone Fracture Cave	Northern Lowland	593
Water Cave	Mixing-Zone Fracture Cave	Median Valley	583
Headless Tourist Pit	Pit Cave	Southeastern Ridge	639
Lasu Recharge Cave	Recharge Cave	North-Central Highland	589
West Lasu Depression Cave	Recharge Cave	Central Plateau	553

Table 28: The caves of Tinian alphabetically by Province

Cave Name	Cave Type	Province	Page Number
Barely Cave	Flank Margin Cave	Central Plateau	523
Cannon Cave	Flank Margin Cave	Central Plateau	525
Cavelet Cave	Flank Margin Cave	Central Plateau	526
Central Mendiola Cave Complex	Flank Margin Cave	Central Plateau	527
Chiget Fracture	Fissure Cave	Central Plateau	520
Cobble Cave	Flank Margin Cave	Central Plateau	530
Cowrie Cave	Flank Margin Cave	Central Plateau	531
Death Fracture	Fissure Cave	Central Plateau	521
Dos Cenotes Cave	Flank Margin Cave	Central Plateau	532
Dos Sakis Cave Complex	Flank Margin Cave	Central Plateau	533
Dump Coke Cave	Flank Margin Cave	Central Plateau	534
Edwin's Ranch Cave	Flank Margin Cave	Central Plateau	536
Flamingo Tail Caves	Flank Margin Cave	Central Plateau	537
Fleming Point Cave	Flank Margin Cave	Central Plateau	538
Half Dozen Cave	Flank Margin Cave	Central Plateau	540
Liyang Diapblo	Flank Margin Cave	Central Plateau	541
Liyang Sampapa	Discharge Feature	Central Plateau	519
Liyang Umumu	Banana Hole	Central Plateau	518
Mendiola Arch Cave Complex	Flank Margin Cave	Central Plateau	542
Monica Wants to be Like Kevin Cave	Flank Margin Cave	Central Plateau	544
Nuestra Senora Complex	Flank Margin Cave	Central Plateau	545
Orange Cave	Flank Margin Cave	Central Plateau	548
Pebble Cave	Flank Margin Cave	Central Plateau	548
Red Snapper Cave	Flank Margin Cave	Central Plateau	549
Rock Hammer Cave	Flank Margin Cave	Central Plateau	550
South Mendiola Cave	Flank Margin Cave	Central Plateau	552
West Lasu Depression Cave	Recharge Cave	Central Plateau	553
Andyland Cave	Flank Margin Cave	Median Valley	561
Barcinas East Cave	Flank Margin Cave	Median Valley	562
Barcinas West Cave	Flank Margin Cave	Median Valley	563
CUC Cave	Banana Hole	Median Valley	555
Dripping Tree Fracture Cave	Fissure Cave	Median Valley	558
Dynasty Cave	Flank Margin Cave	Median Valley	564
Gecko Cave	Discharge Feature	Median Valley	556
Hidden Beach Cave	Flank Margin Cave	Median Valley	565
Johns Small Cave	Flank Margin Cave	Median Valley	567
Leprosy Cave	Flank Margin Cave	Median Valley	568
Leprosy Discharge Feature	Discharge Feature	Median Valley	557
Liyang Dangkolo	Flank Margin Cave	Median Valley	569
Metal Spike Cave	Flank Margin Cave	Median Valley	571
North Unai Dangkolo	Flank Margin Cave	Median Valley	575

Table 28 (Continued)

Cave Name	Cave Type	Province	Page Number
Plunder Cave	Mixing-Zone Fracture Cave	Median Valley	581
South Unai Dangkolo	Flank Margin Cave	Median Valley	577
Swimming Hole Complex	Flank Margin Cave	Median Valley	578
Unai Masalok	Flank Margin Cave	Median Valley	579
Water Cave	Mixing-Zone Fracture Cave	Median Valley	583
Command Post Cave	Flank Margin Cave	North-Central Highland	586
Lasu Recharge Cave	Recharge Cave	North-Central Highland	589
Liyang Gntot	Flank Margin Cave	North-Central Highland	587
Metal Door Cave	Flank Margin Cave	North-Central Highland	588
Rootcicle Cave	Banana Hole	North-Central Highland	585
Rogue Cave	Discharge Feature	Northern Lowland	591
Unai Chiget	Mixing-Zone Fracture Cave	Northern Lowland	593
Unai Lamlam	Flank Margin Cave	Northern Lowland	592
"600 M" Fracture Caves	Mixing-Zone Fracture Cave	Southeastern Ridge	636
Bee Hooch Cave	Flank Margin Cave	Southeastern Ridge	602
Body Rapel Cave	Flank Margin Cave	Southeastern Ridge	605
Broken Stal Cave	Flank Margin Cave	Southeastern Ridge	606
Carolina's Fracture Cave	Fissure Cave	Southeastern Ridge	595
Cave Without a Cave	Flank Margin Cave	Southeastern Ridge	608
Cave Without a Roof	Flank Margin Cave	Southeastern Ridge	608
Cetacean Cave	Discharge Feature	Southeastern Ridge	595
Coconut Trap Cave	Flank Margin Cave	Southeastern Ridge	609
Danko's Misery	Fissure Cave	Southeastern Ridge	596
East Suicide Cliff Cave	Flank Margin Cave	Southeastern Ridge	610
Elevator Cave	Flank Margin Cave	Southeastern Ridge	611
False Floor Cave	Flank Margin Cave	Southeastern Ridge	612
Five Bee Cave Complex	Flank Margin Cave	Southeastern Ridge	613
Full Bottle Cave	Fissure Cave	Southeastern Ridge	597
Headless Tourist Pit	Pit Cave	Southeastern Ridge	639
Hermit Crab Cave	Flank Margin Cave	Southeastern Ridge	614
Liyang Barangka	Flank Margin Cave	Southeastern Ridge	615
Liyang Mohlang	Flank Margin Cave	Southeastern Ridge	617
Liyang Popporput	Fissure Cave	Southeastern Ridge	599
Lower Suicide Cliff Cave Complex	Flank Margin Cave	Southeastern Ridge	618
Masalok Fracture Cave Complex	Fissure Cave	Southeastern Ridge	600

Table 28 (Continued)

Cave Name	Cave Type	Province	Page Number
Metal Strecher Cave	Flank Margin Cave	Southeastern Ridge	621
Modified Cave	Flank Margin Cave	Southeastern Ridge	622
Northern Playground Cave	Flank Margin Cave	Southeastern Ridge	623
Pina Cave Complex	Flank Margin Cave	Southeastern Ridge	624
Playground Cave	Flank Margin Cave	Southeastern Ridge	626
Radio Inactive Cave	Flank Margin Cave	Southeastern Ridge	627
Skip Jack Cave	Flank Margin Cave	Southeastern Ridge	628
Skull Cave Complex	Flank Margin Cave	Southeastern Ridge	630
Skylight Cave	Flank Margin Cave	Southeastern Ridge	631
Solitary Cave	Flank Margin Cave	Southeastern Ridge	633
Twin Ascent Caves	Flank Margin Cave	Southeastern Ridge	633
West Suicide Cliff Caves	Flank Margin Cave	Southeastern Ridge	634

CENTRAL PLATEAU

Banana Hole

Liyang Umumu

Liyang Umumu is located 900 meters north/northeast of *Puntan Diapblo* in the Mariana Limestone (QTmu), less than 3 meters below the land surface. It is a banana hole type cave with an average height of 1 meter, depth of 3.5 meters and entrance width of 11 meters. This small feature contains extensive speleothems including flowstone covering all walls and the floor in the northeast portion of the cave, several columns, and numerous stalactites covering the majority of the ceiling. The floor is primarily composed of soil and detritus with some scattered breakdown blocks.

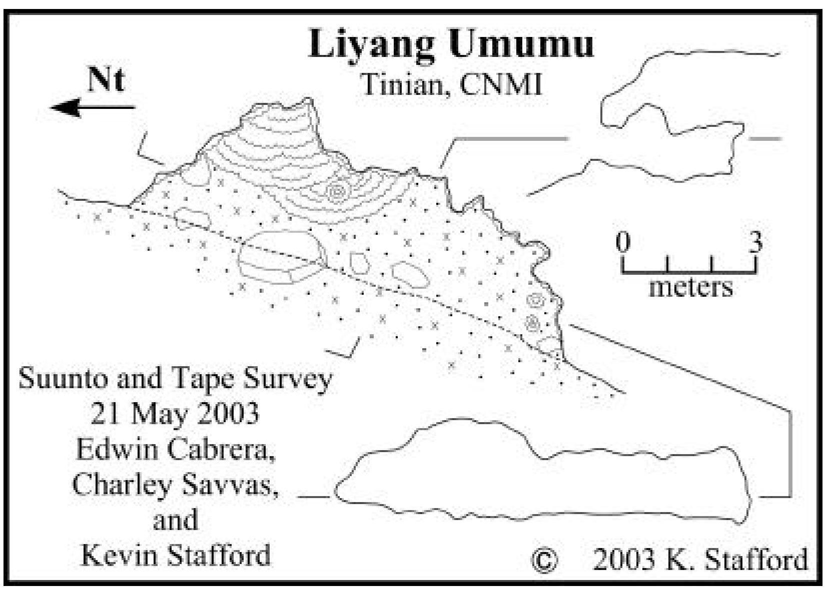

Figure 276: Map of Liyang Umumu

Discharge Features

Liyang Sampapa

Liyang Sampapa is located 250 meters south of *Puntan Lamanibot Sampapa* on the west coast. It is developed in the Mariana Limestone (QTmca) and extends inland 20 meters with a width of 8 meters and a bedrock floor. The entrance area of the cave is below sea level. The feature appears to be developed along an east/west trending joint trending that is well defined on the land surface, but less defined inside the cave. The feature appears to discharge minor amounts of fresh-water, but a definitive observation of discharge could not made at the time of survey because of strong surf conditions.

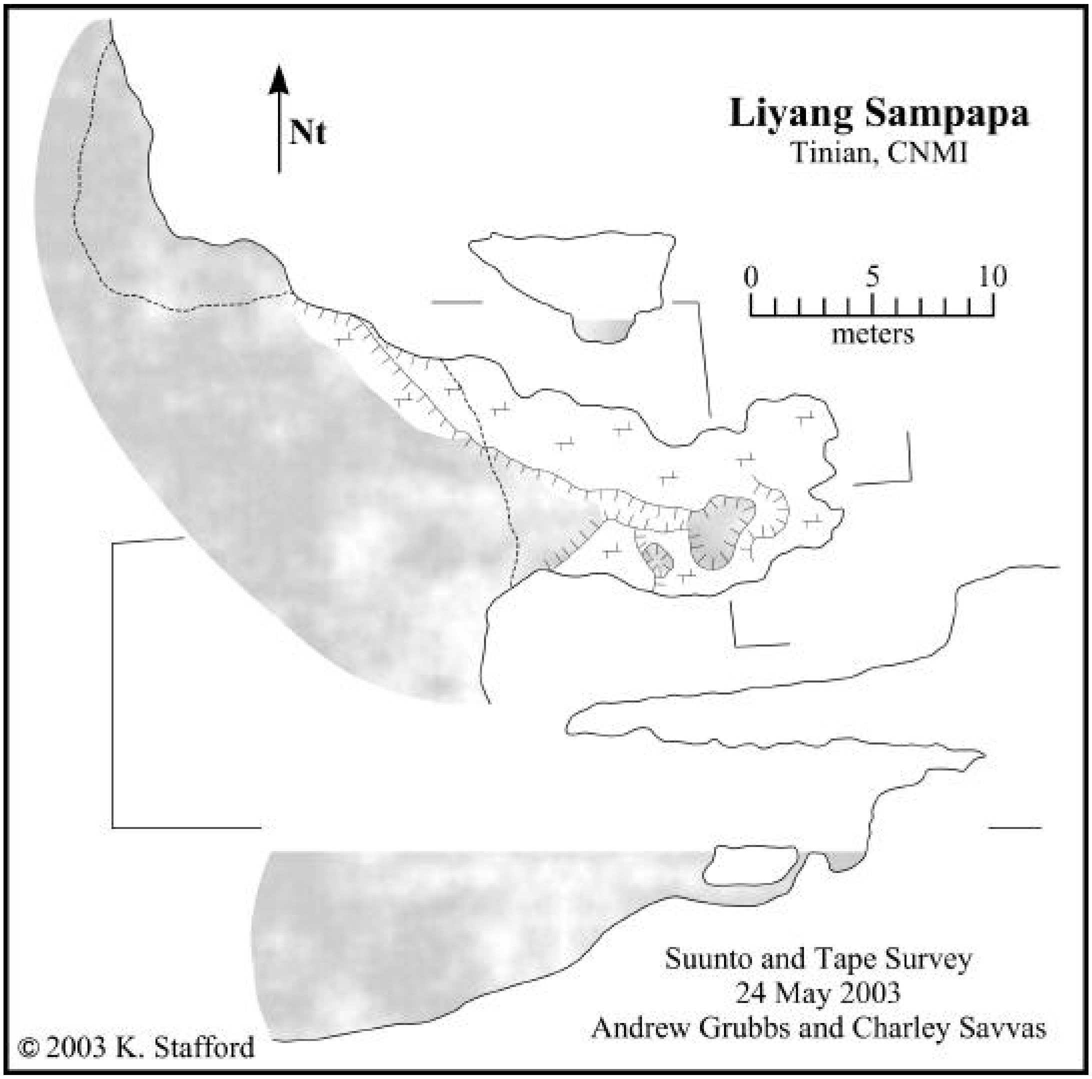

Figure 277: Map of Liyang Sampapa

Fissure Caves

Chiget Fracture

Chiget Fracture is located on the southern wall of the *Unai Chiget* Fault scarp, approximately 500 meters inland. It is developed in the Mariana Limestone (QTmu) and is a dissolutionally widened fracture that is oriented northeast (~50 °) and intersected by a smaller fracture oriented east/southeast (~105 °) in the inland portion. The main fracture is approximately 20 meters long, 1.5 meters wide, and 15 meters deep. In the inland portion, the fracture is blocked by breakdown, which forms a small roofed portion, but no speleothems are present. The small fracture extends for over 6 meters and is less than 0.5 meters wide. These dissolutionally widened fractures are the result of cliff retreat associated with fracturing at the cliff margin.

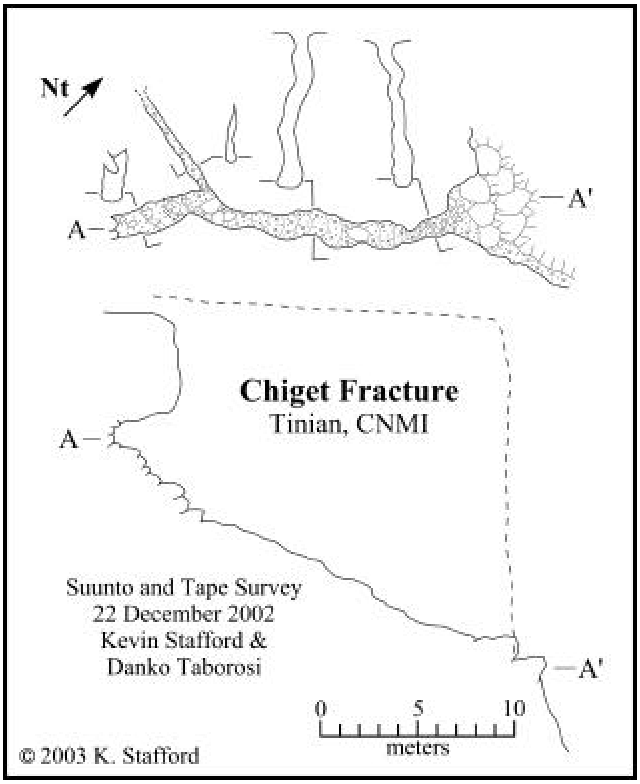

Figure 278: Map of Chiget Fracture

Death Fracture Complex

The Death Fracture Complex is located along the west coast approximately 900 meters south of *Puntan Diapblo* in the Mariana Limestone (QTmu). This fracture complex contains three primary features, which extend inland as dissolutionally widened fractures oriented at 53^o, 60^o, 80^o, and 112^o with an average depth to sea level of 8 meters. The features are widest near the coastline and decrease in width with distance inland, however all features extend well below sea-level and are severely impacted by normal wave attack, which limited exploration to surface observations at the time of survey. The features appear to have well-developed ledges at sea level, but the cave then appears to widen below sea level. Because of their similarity to features seen on Guam (No-Can Cave, Taborosi, 2000) and their development along prominent regional fractures, these features are interpreted as structurally controlled, fresh-water discharge features although strong surf conditions, which would surge over 4 meters upwards into the features, prevented physical observation of fresh-water discharge.

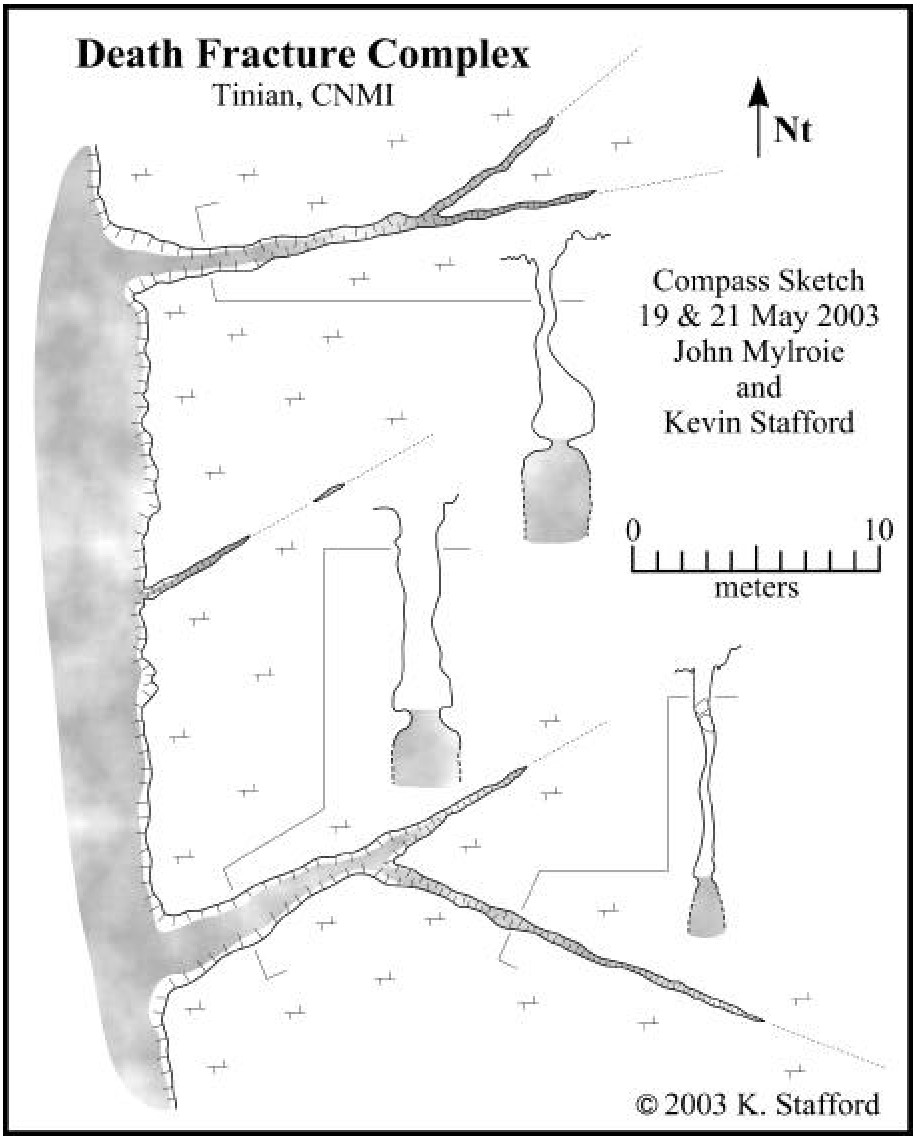

Figure 279: Map of Death Fracture Complex.

Flank Margin Caves

Barely Cave

Barely Cave is a remnant, flank margin cave that is located approximately 600 meters southeast of *Puntan Diapblo* at sea-level in the Mariana Limestone (QTmu). The cave is 38 meters wide and 18 meters deep and appears to have been severely impacted by intense storm events. The majority of the feature is unroofed, with a partial roof existing on the southeast side of the feature in the region were the cave floor is below sea level. The northern portion of the feature has a bedrock floor, while minor amounts of heavily eroded flowstone exist on the floor of the east-central portion of the cave. Although heavily impacted by coastal processes, the presence of flowstone confirms a spelean origin for the feature.

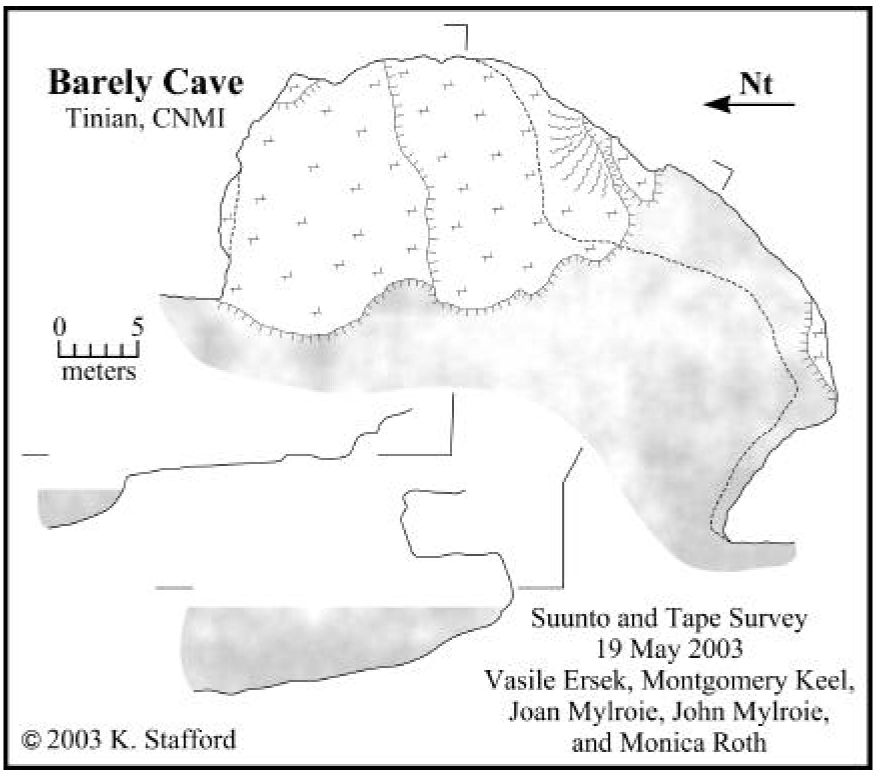

Figure 280: Map of Barely Cave

Cannon Cave

Cannon Cave is a modified flank margin cave formed in the Mariana Limestone (QTmu). It is located approximately 2 kilometers east of *Puntan Diapblo*, approximately 300 meters north of the coast. The cave was modified and used as a defensive position by the Japanese during World War II and still contains a 5-meter long, 16-centimeter Japanese gun. The natural chamber is 5 meters by 12 meters with a ceiling height of 5 meters. Extending to the East is a 5-meter long, 1.5-meter square dug, tunnel probably used to store ammunition. This feature appears to have had little modification to the ceiling and the walls of the main chamber, but the floor appears to have had significant modification for use as a defensive position.

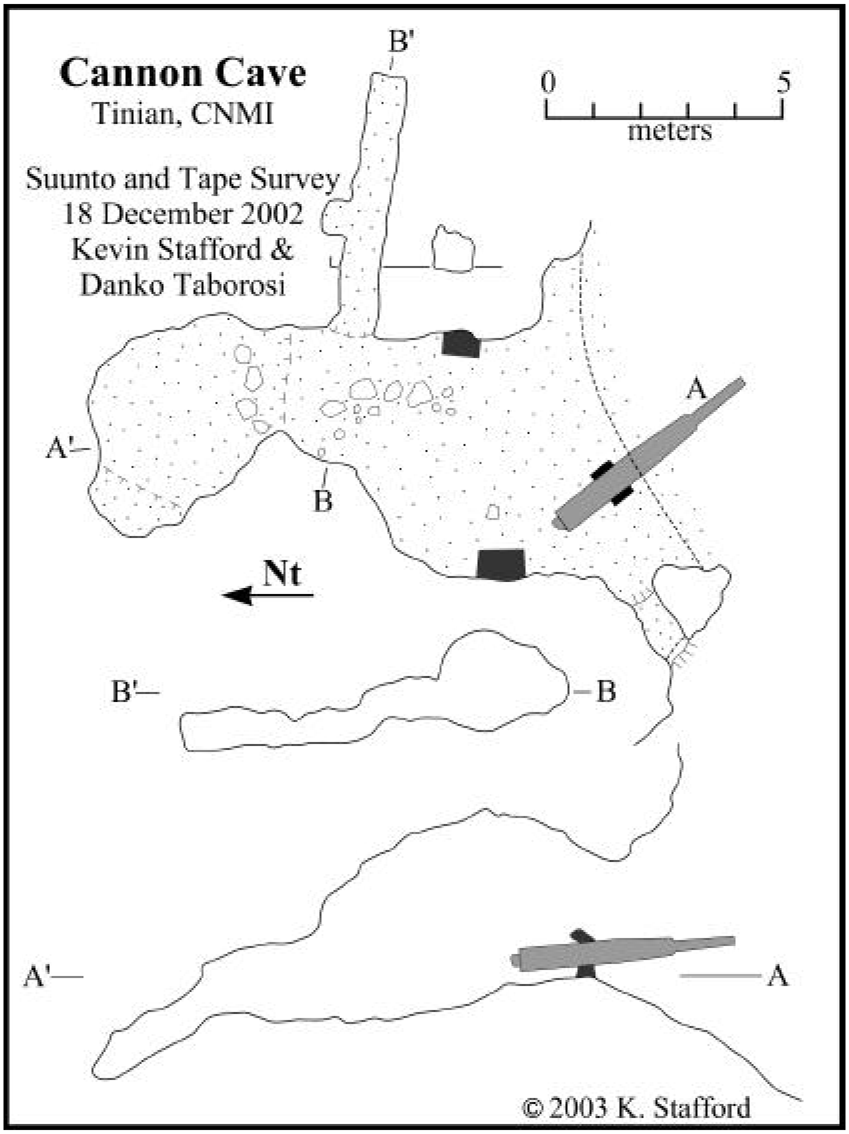

Figure 281: Map of Cannon Cave

Cavelet Cave

Cavelet Cave is a small, remnant, flank margin cave located approximately 500 meters southeast of *Puntan Diapblo*. The cave, developed in the Mariana Limestone (QTmu), has an entrance 4 meters wide, extends inland 5 meters, and has an average ceiling height of 1.5 meters. The cave is located 3 meters above sea level and approximately 100 meters inland. The floor is composed of bedrock with small breakdown blocks, while the cave is devoid of speleothems, possibly as a result of intense storm events.

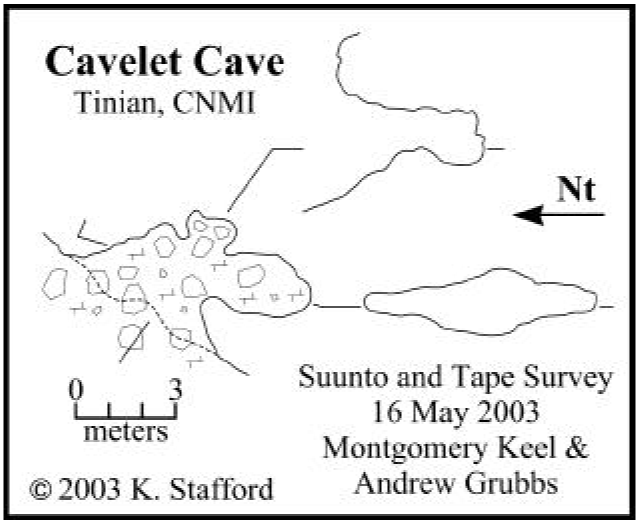

Figure 282: Map of Cavelet Cave

Central Mendiola Cave Complex

Central *Mendiola* Cave Complex is located in the central region of a large cove approximately 800 meters southeast of *Puntan Atgidon*, which is locally referred to as *Mendiola* Cove after the landowner. This cave complex is developed in the Mariana Limestone (QTmu) and covers 150 meters of coastline. The breached, flank margin caves extend inland up to 20 meters with and average ceiling height of 4 meters. They are located slightly above mean sea level and primarily contain bedrock floors with weathered breakdown blocks and cobbles.

Smaller cave chambers exist at the north and south ends of the surveyed cave complex with the largest chamber located in the central region. The largest chamber has an entrance 50 meters wide and extends inland 15 meters as a single large chamber. There is a sea stack located at its southern margin that may represent a previous bedrock column. To the south of the largest cave, the deepest cave extends inland 20 meters with average width of 8 meters, while to the north of the largest cave a chamber divided by a 2 meter wide, 10 meter long bedrock column extends inland 15 meters. This series of breached, flank margin caves appear to have been connected as a single cave in the past based on the proximity of the individual cave remnants and their corresponding ceiling drip lines.

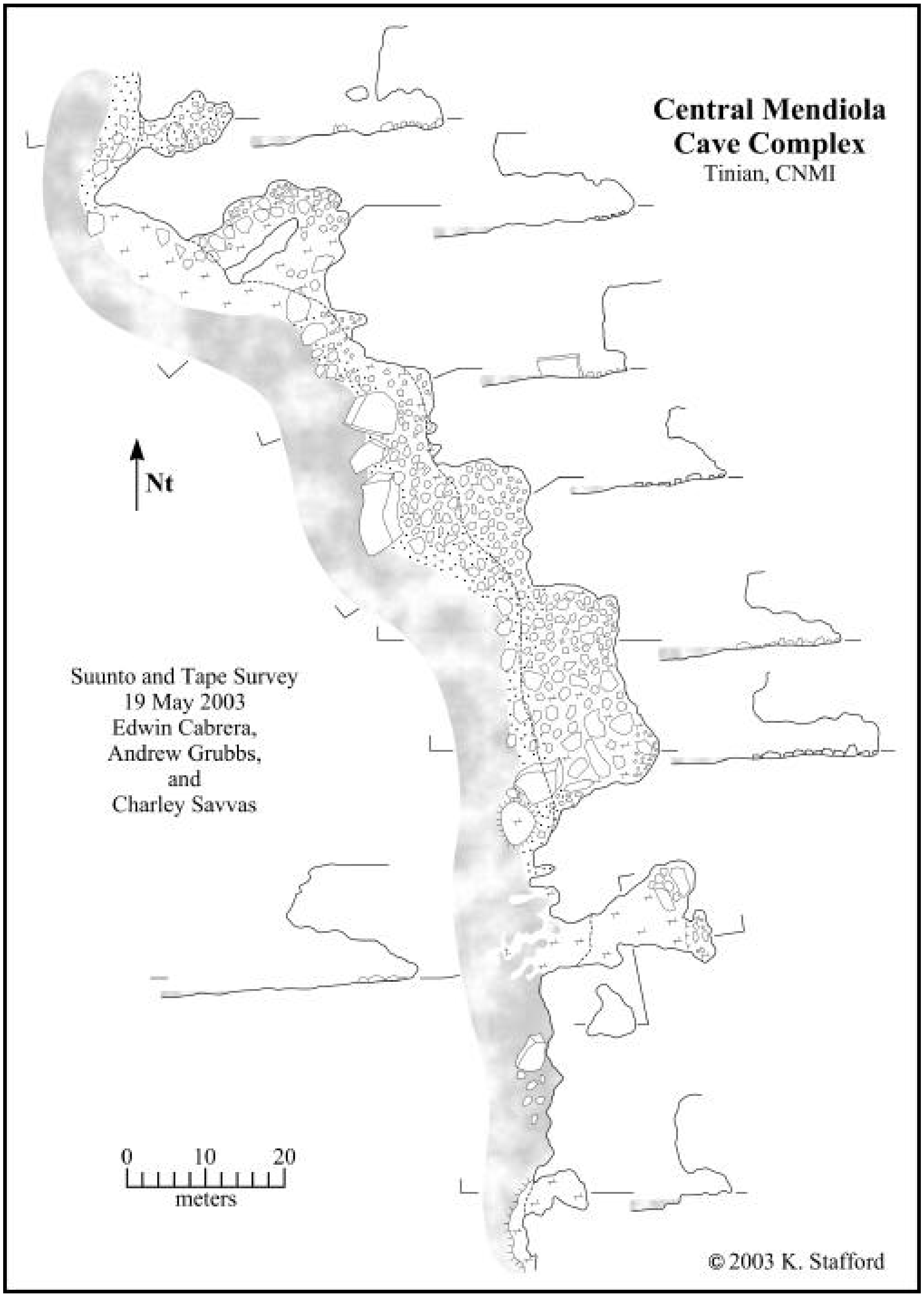

Figure 283: Map of Central Mendiola Cave Complex

Cobble Cave

Cobble Cave is located 650 meters southeast of *Puntan Atgidon* in the Mariana Limestone (QTmu). It is a flank margin cave remnant located approximately 1 meter above sea level in the northeastern portion of a large cove referred to locally as *Mendiola* Cove after the landowner. The entrance is 19 meters wide and the cave extends inland 11 meters with an average ceiling height o f 4 meters. The floor is primarily composed of carbonate sand but numerous well-round cobbles and breakdown blocks are scattered around the chamber, some of which appear to be remnants of the original ceiling that extended farther seaward.

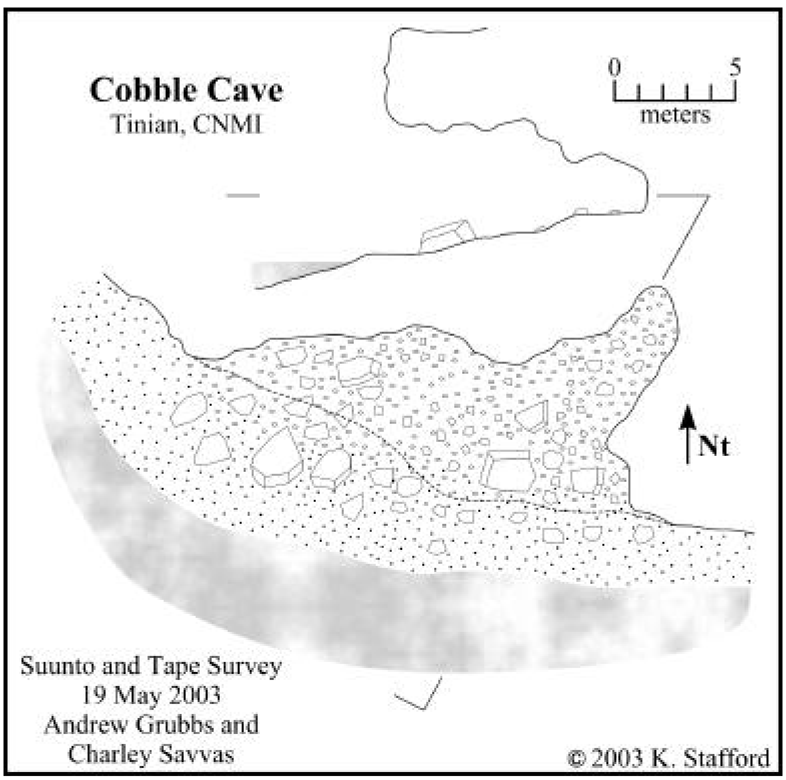

Figure 284: Map of Cobble Cave

Cowrie Cave

Cowrie Cave is located approximately 500 meters southeast of *Puntan Atgidon* on the northern edge of a large cove locally referred to as *Mendiola* Cove after the landowner. This bedrock floored cave is a breached flank margin cave positioned less than 1 meter above mean sea level. The cave is 8 meters wide and 16 meters deep with a maximum ceiling height of 7 meters. A prominent fracture trends 113°, parallel to the entrance, approximately 5 meters inland and has produced 2 meter deep dissolutional features in the east and west walls of the cave. The cave is named for several large cowries that were living in a small pool of water at the time of survey.

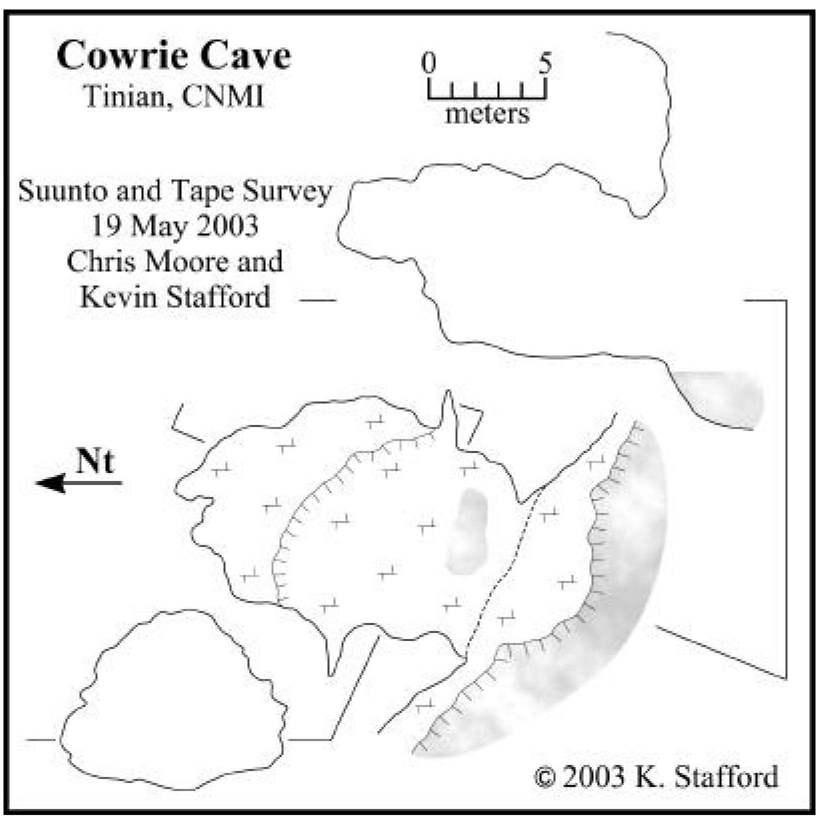

Figure 285: Map of Cowrie Cave

Dos Cenotes Cave

Dos Cenotes Cave is located approximately 450 meters southeast of *Puntan Atgidon* in the northwest corner of a large cove locally referred to as *Mendiola* Cove after the landowner. The 45-meter wide, south facing entrance opens to the ocean and is protected by headlands projecting from the southeast and southwest sides. In the northeast portion, the cave extends inland 15 meters as a terraced chamber with a large bedrock column in the middle. In the northwest portion, the cave extends inland 12 meters with two bedrock columns located near the entrance. From the northwest portion of the cave, a passage averaging 3 meters wide extends to the west for 30 meters where it connects to the surface through a skylight entrance and to the ocean through a submerged passage. The cave primarily contains bedrock floors, but breakdown blocks and minor speleothem deposits are found throughout. The cave is named after two pools of water approximately 3 meters deep, which are located southwest of the main entrance area.

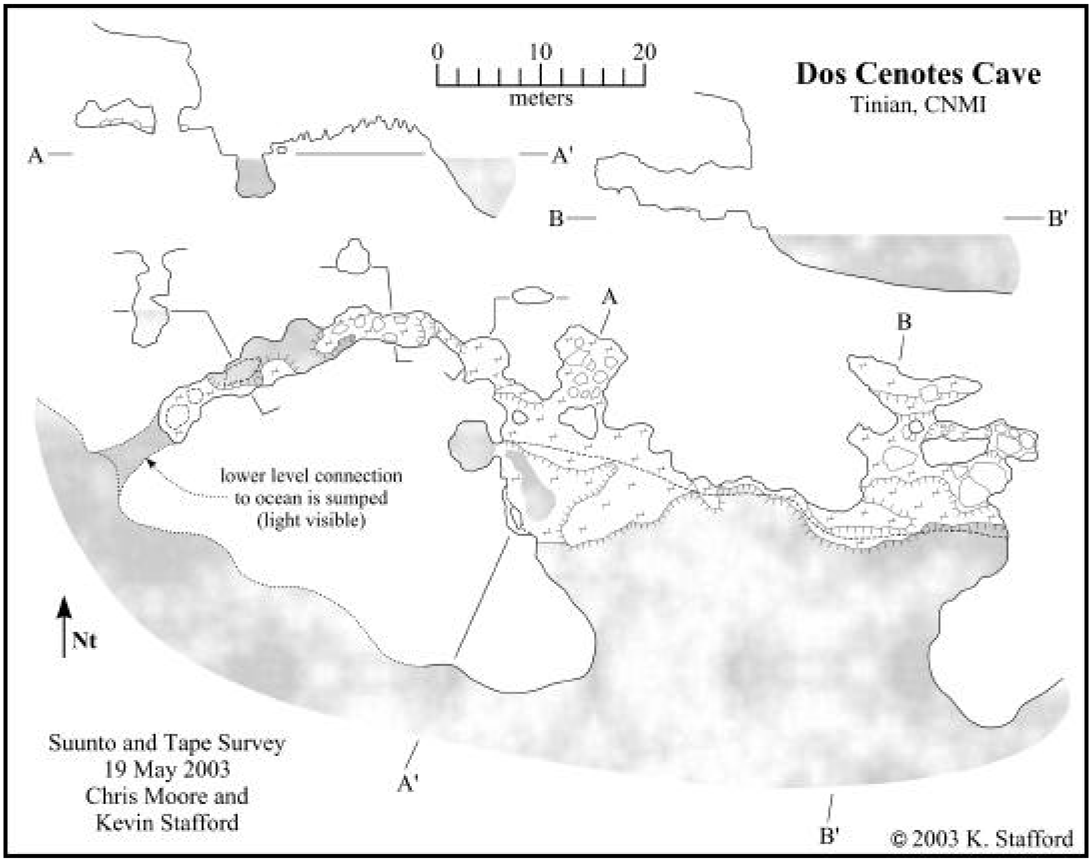

Figure 286: Map of Dos Cenotes Cave

Dos Sakis Cave Complex

Dos Sakis Cave Complex consists of five breached, flank margin caves located approximately 1000 meters east of *Puntan Diapblo* along a 9-meter tall scarp in the Mariana Limestone (QTmu). The caves extend inland a maximum of 5 meters with an average ceiling height of 3 meters. The most western and smallest cave in the complex is slightly elevated on the scarp wall. The two eastern most caves are simple chambers that show minor human modification including a partial rock wall. The two central caves, extend the farthest inland and show greater human modification. The western of the two has a 1-meter wide and 1-meter deep trench extending from the entrance to the back wall of the cave. The eastern central cave is the largest and has a depression 1 to 1.5 meters deep and almost 5 meters in diameter excavated in the entrance area, while the cave floor rises 2 meters in the inland portion. The caves in this complex have floors primarily of soil and detritus with occasional breakdown blocks and all appear to have been partially to extensively modified by humans.

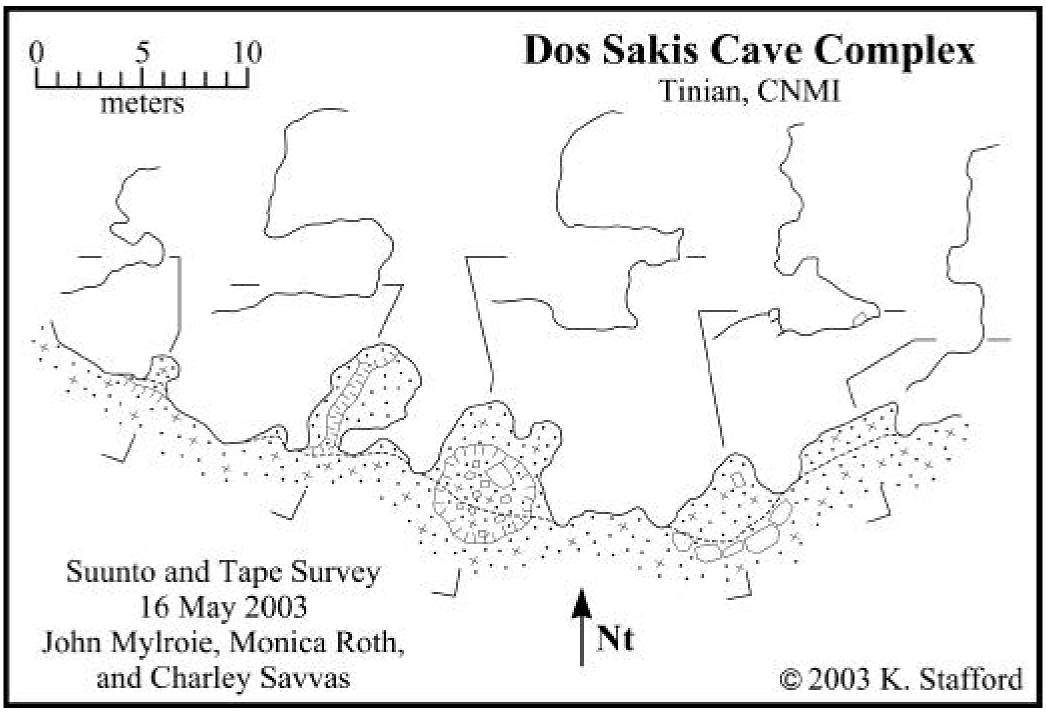

Figure 287: Map of Dos Sakis Cave Complex

Dump Coke Cave

Dump Coke Cave is located 700 meters south/southeast of *Puntan Lamanibot* Sanhilo in *Lamanibot* Cove, which is locally referred to as Dump Coke because of the numerous soda bottles that were disposed of there during World War II. This breached flank margin cave, which extends inland 21 meters with and entrance width of 6 meters, is developed in the Mariana Limestone (QTmu). The cave has a maximum ceiling height of 11 meters and a floor covered in heavily weathered breakdown blocks. From the inland portion of the main chamber, a small, tube-like passage extends inland 4 meters and turns abruptly north for and additional 3 meters before terminating. This tube is 3 meters above the floor of the main chamber and has a bedrock floor for the majority of its length.

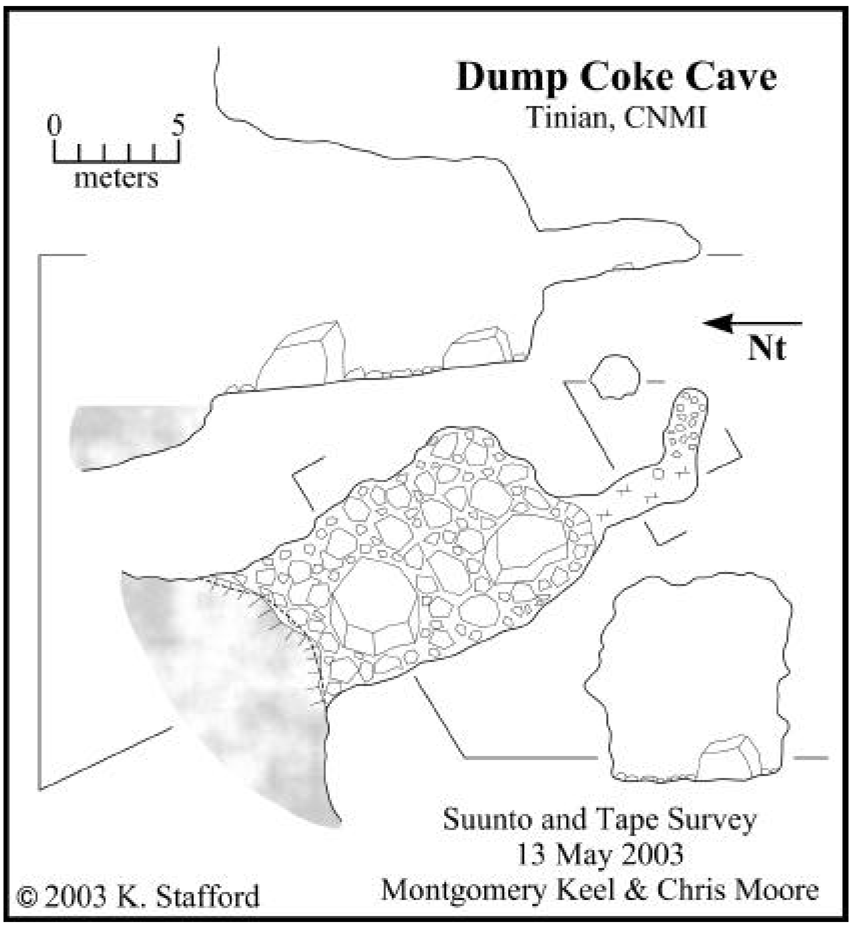

Figure 288: Map of Dump Coke Cave

Edwin's Ranch Cave

Edwin's Ranch Cave is located approximately 1200 meters south of *Unai Lamanibot* and approximately 800 meters east of the coastline. This flank margin cave is developed in the Mariana Limestone (QTmcc) and has been breached by cliff retreat. The cave appears to be nearly complete, with 3 small entrances that are less than 1 meter high on the northern margin of the cave. The cave is 3 meters tall, 9 meters wide, and 12 meters long. In the southeast portion of the cave, there are two small side chambers, while the entrances appear to be similar features that were breached. Speleothems in the cave are limited and the floor is composed primarily of alluvium of indeterminate depth. The two northwest entrances show evidence of human excavation, which makes access into the feature possible, but the northeast entrance has not been modified and is less than 10 centimeters tall.

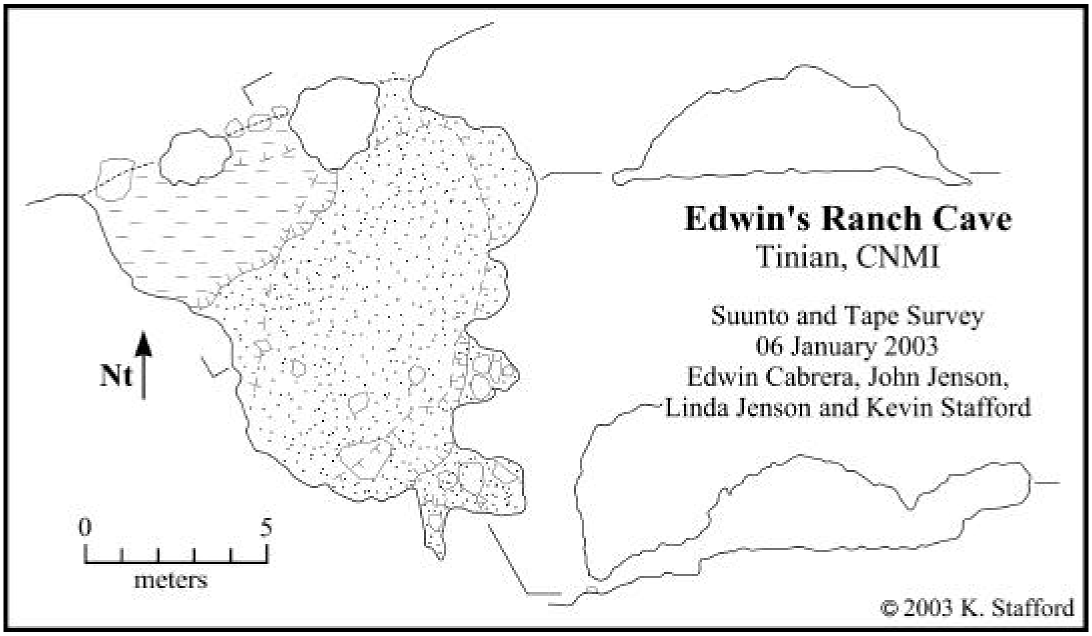

Figure 289: Map of Edwin's Ranch Cave

Flamingo Tail Caves

Flamingo Tail Caves are located 900 meters west/southwest of *Puntan Diapblo* along a small intermittent scarp in the Mariana Limestone (QTmu). This section of scarp contains two caves and a series of well-defined notches that may represent other flank margin cave remnants where the ceiling has completely collapsed. The eastern portion of the scarp segment contains a cave with three distinct passages, averaging 2 meters in height that radiate from a central entrance area; one extends east 8 meters, one extends northeast 7 meters and one extends north 4 meters. On the western edge of the scarp segment, a small remnant cave extends inland 2 meters with a width of 4 meters and height of 0.5 meters. The ground surface along the scarp and inside the caves is composed of soil and detritus with some minor breakdown blocks in the eastern cave.

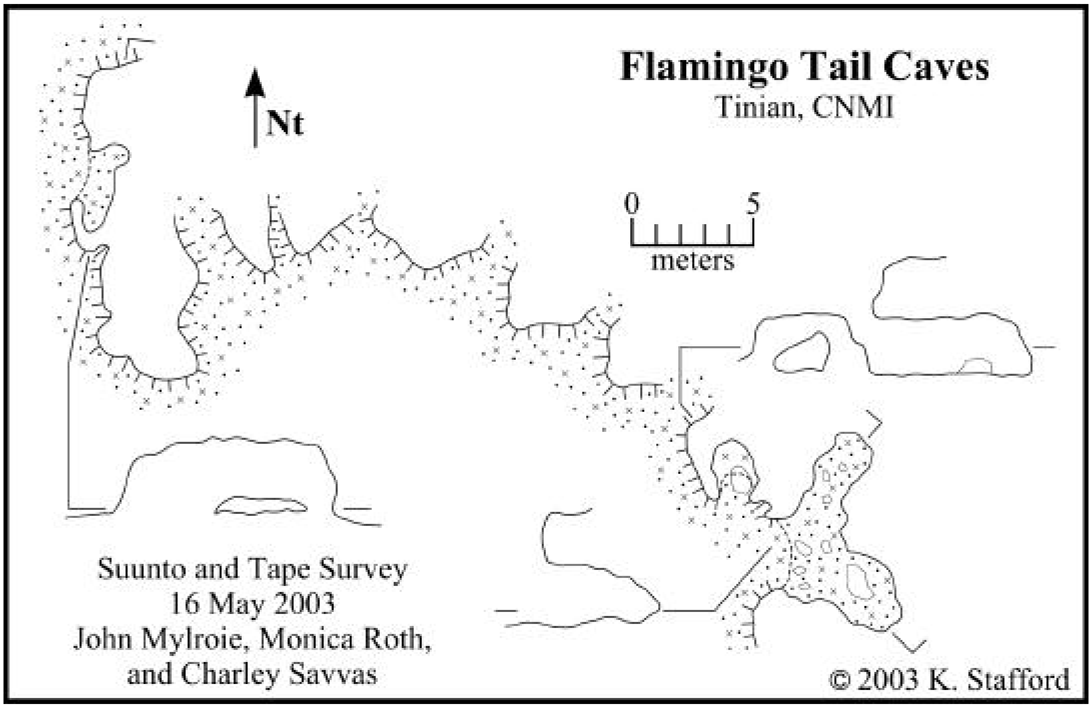

Figure 290: Map of Flamingo Tail Caves

Fleming Point Cave

Fleming Point Cave is located 700 meters north/northeast of *Puntan Atgidon* in a small cove developed in the Mariana Limestone (QTmu). The cave is developed along a prominent fracture or joint that is well defined in the ceiling and floor of the cave throughout the 41 meters that the cave extends inland. The cave has an entrance height of 11 meters and decreases to 6 meters, 13 meters inland from the entrance. The cave has two prominent dissolutional pockets that deviate from its linear passage; one located on the east side at 9 meters inland and one on the west side at 22 meters inland. The cave is primarily bedrock floored, but contains some large breakdown blocks in the inland portions. Based on the general morphology of the cave, its development along a prominent zone of brittle failure and observable scheiren mixing of the water near the entrance, this feature is interpreted as a structurally controlled discharge feature.

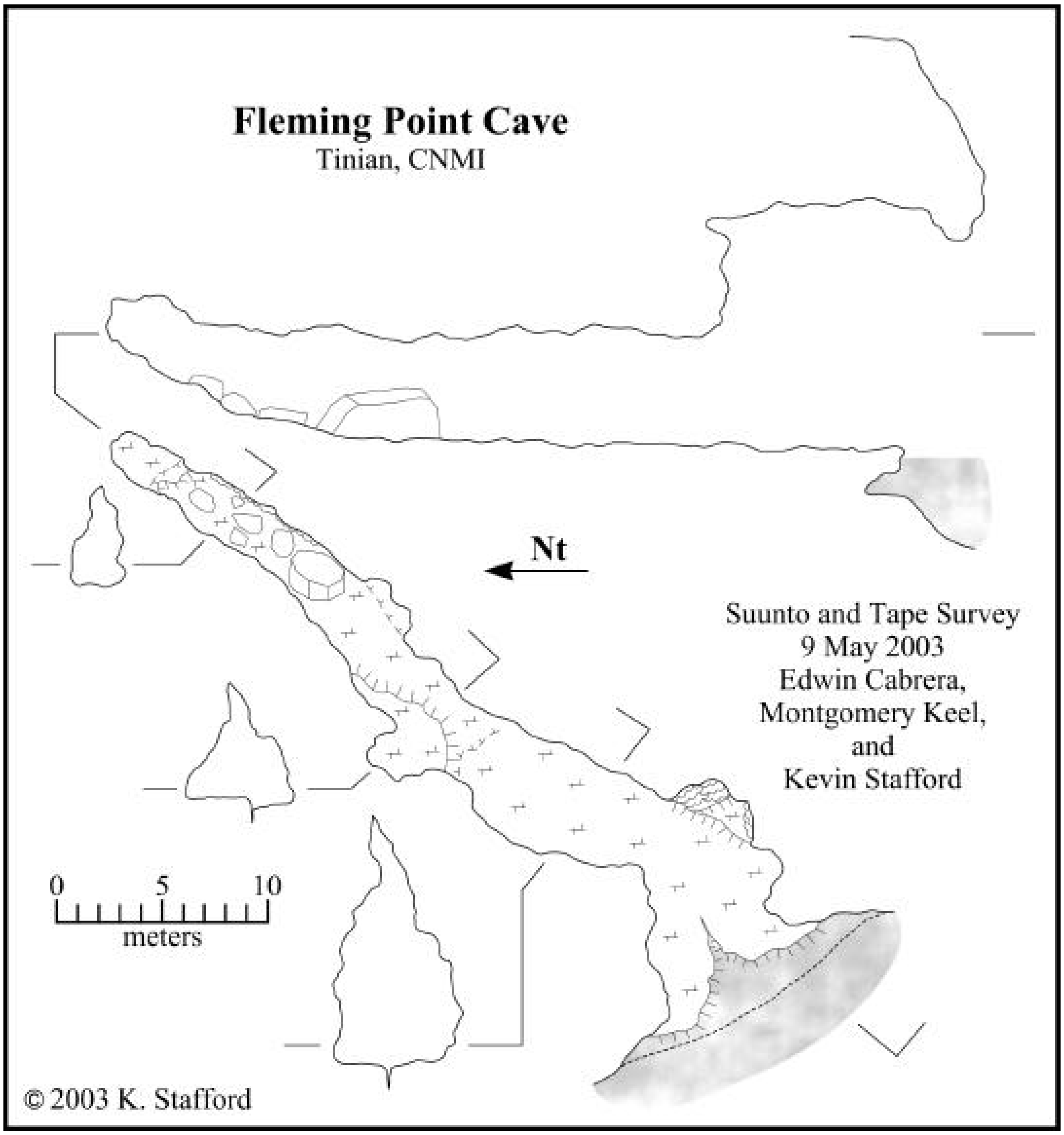

Figure 291: Map of Fleming Point Cave

Half-Dozen Cave

Half-Dozen Cave is a breached flank margin cave located approximately 2 kilometers east of *Puntan Diapblo* and approximately 300 meters north of the coast. It is developed in the Mariana Limestone (QTmu) and appears to have been infilled with limestone aggregate. The cave is entered at the top of a scree slope along the cliff edge, which forms an angle of approximately 35° to the cliff and descends at a 35° slope into the cave near the cave's roof. The cave is 8 meters long and 7 meters wide with some minor speleothems in interior portions and exterior cliff wall. The feature is thought to be more extensive based on the occurrence of additional speleothems on the cliff wall, but much of the entrance appears to be currently blocked by the loose aggregate.

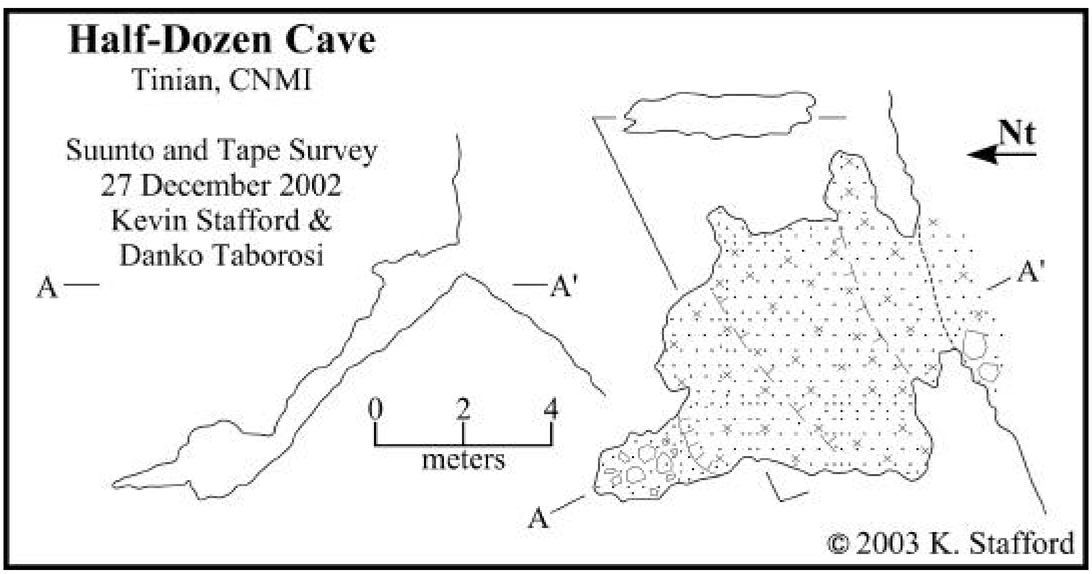

Figure 292: Map of Half-Dozen Cave

Liyang Diapblo

Liyang Diapblo is a large, breached, flank margin cave on the western coast, 300 meters southeast of *Puntan Diapblo* in the Mariana Limestone (QTmu). The entrance to the feature a small cove, 40 meters wide that extends inland 70 meters with a large bedrock mass (12 meters wide by 35 meters long) in the middle. The cave is divided into several areas. South of the large bedrock mass, the feature contains no roof and extends up to 4 meters below sea level. East of the bedrock mass is a small chamber that extends inland 8 meters with a height of 4 meters. Northeast of the bedrock mass is a large passage with a breakdown covered floor that extends 30 meters with and average width of 8 meters and average ceiling height of 6 meters. Northwest of the bedrock mass is a large chamber 15 meters wide, 20 meters deep and 8 meters tall that contains a large flowstone mound 4 meters tall in the center of the chamber and several smaller flowstone deposits around the periphery of the chamber. Directly north of the bedrock mass is a series of smaller interconnected passages leading to the eastern and western parts of the cave. This cove appears to have formed by roof collapse of the flank margin cave that consisted of a large chamber with several smaller side chambers separated from main chamber by a large bedrock pillar.

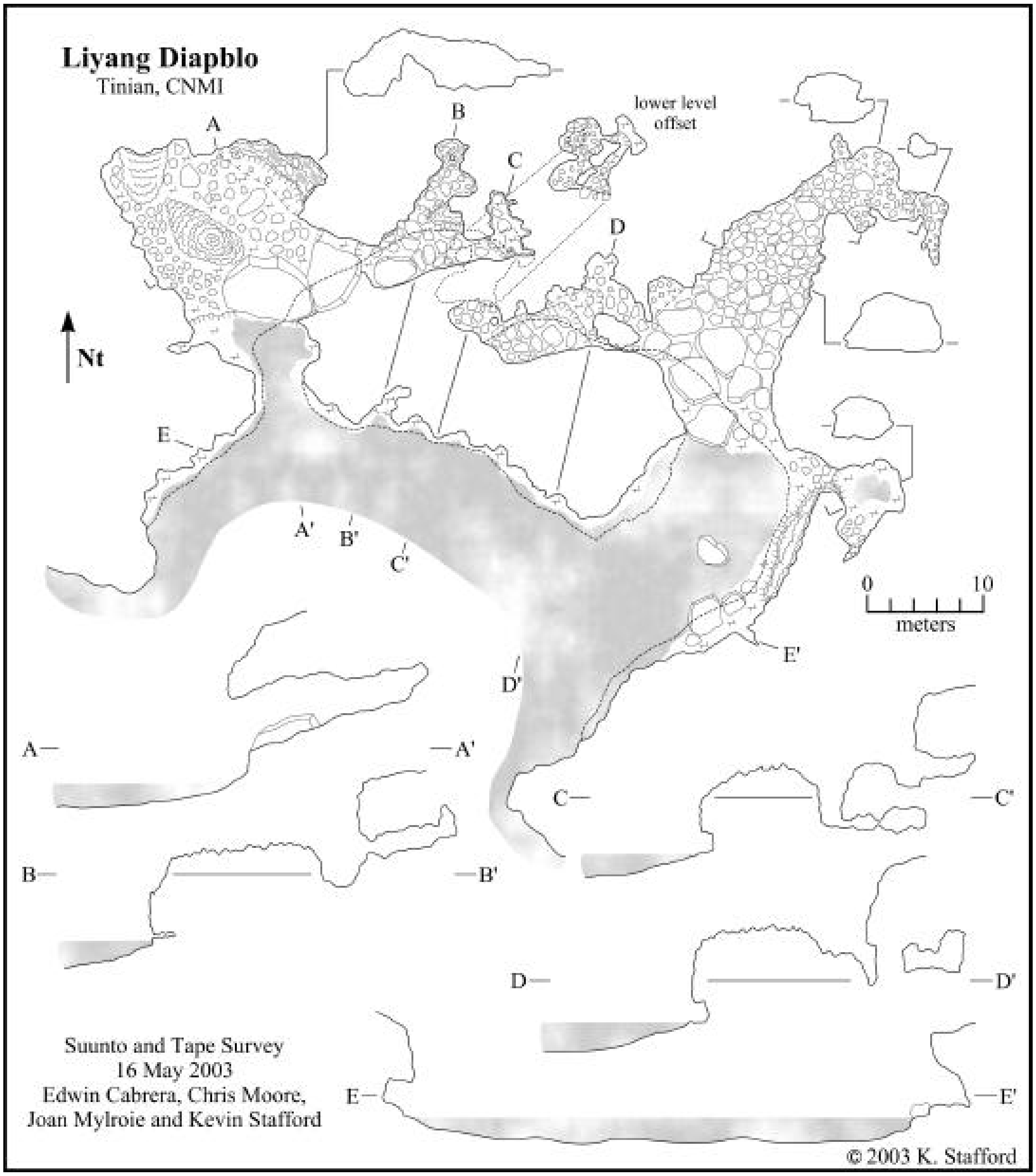

Figure 293: Map of Liyang Diapblo

Mendiola Arch Cave Complex

Mendiola Arch Cave Complex is located 1200 meters southeast of *Puntan Atgidon* on the southern edge of a large cove referred to locally as *Mendiola* Cove after the name of the landowner. It is a series of breached, flank margin caves developed in the Mariana Limestone (QTmu). The complex is split into two areas by a cave remnant that forms a natural arch that is 6 meters wide and 10 meters tall. Northeast of the arch is a series of four cave chambers which range from 5 to 15 meters wide and extend inland up to 20 meters with and average ceiling height of 5 meters. South of the natural arch, two larger caves have entrance widths of 18 and 24 meters and extend inland up to 25 meters. The caves in this complex primarily contain bedrock floors with breakdown blocks and cobbles. Based on the proximity of the features, it appears that some, if not all of the features were connected in the past and have been isolated as individual cave remnants by erosional, coastal processes.

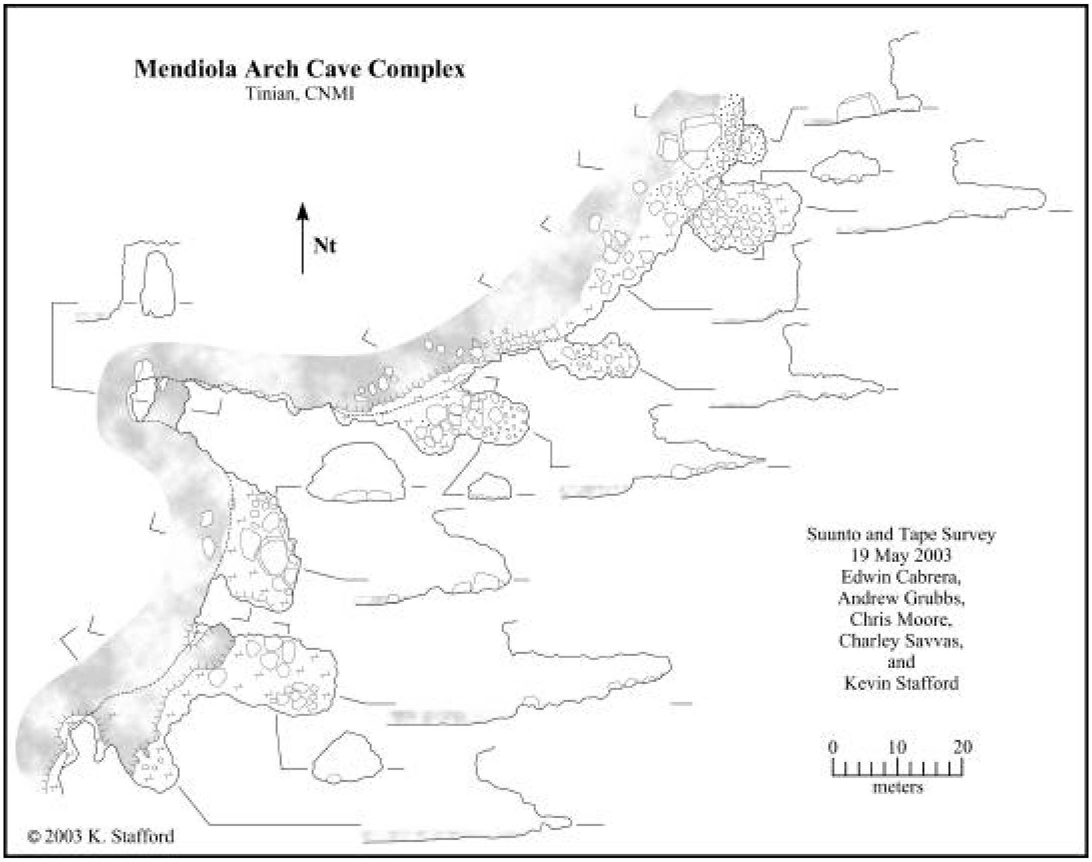

Figure 294: Map of Mendiola Arch Cave Complex

Monica Wants to be Like Kevin Cave

Monica Wants to be Like Kevin Cave is located 800 meters east of *Puntan Diapblo* in the Mariana Limestone (QTmu). This flank margin cave remnant has an entrance 11 meters wide and extends inland 12 meters where it widens to 14 meters. The ceiling height averages 5.5 meters but decreases inland. The floor is composed of soil and detritus with a moderate amount of breakdown blocks in the middle of the cave.

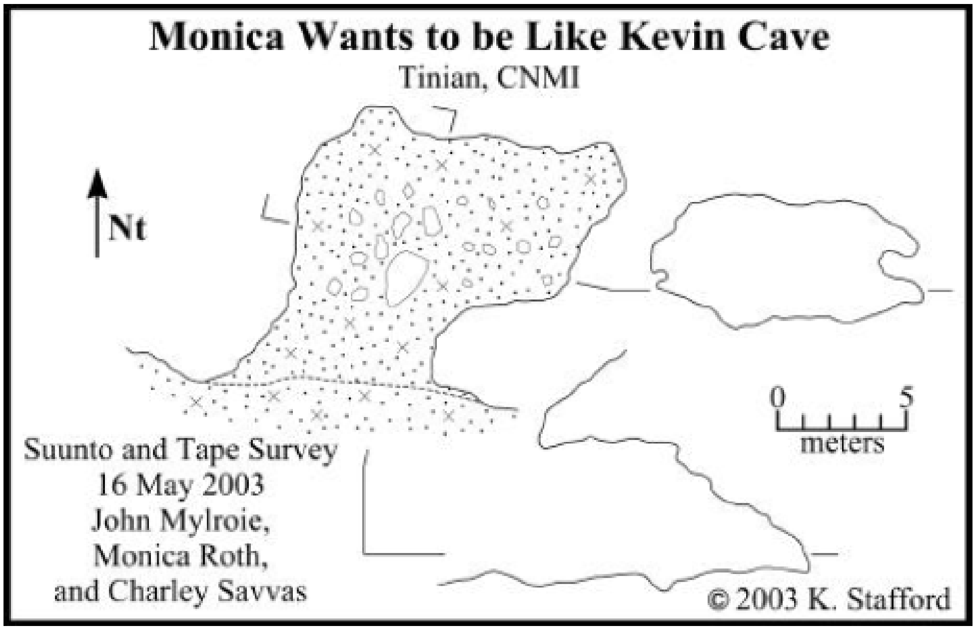

Figure 295: Map of Monica Wants to be Like Kevin Cave

Nuestra Señora de Santa Lourdes Cave Complex

This cave complex, including the Nuestra Señora de Santa Lourdes shrine located at feature "C", consists of a series of flank margin caves that developed on a consistent horizon and were modified for use during World War II. This series of caves is developed in the Mariana Limestone (QTmu) and have been breached by cliff retreat at the boundary between the Median Valley and Central Plateau. The caves vary in size and degree of human modification. Features A, C and D are typical flank margin caves with minor excavation to their floors, while the ceilings and walls appear to have been modified little, except for feature C, which has two small side passages that where excavated. Feature B has been highly modified leaving little evidence of the original floor, ceiling, or walls, making its origin unclear. Feature E is extensively modified, including cement floor and supporting walls, as well as widened regions that are reinforced with concrete. It is doubtful that much of this feature is of original dissolutional origin, because of the constant height of the chamber at 1.6 meters and the extensive talus debris located outside its eastern entrance. In addition to the modifications during the World War II Japanese occupation, feature C has a modified floor of limestone aggregate and a cement shrine it the center.

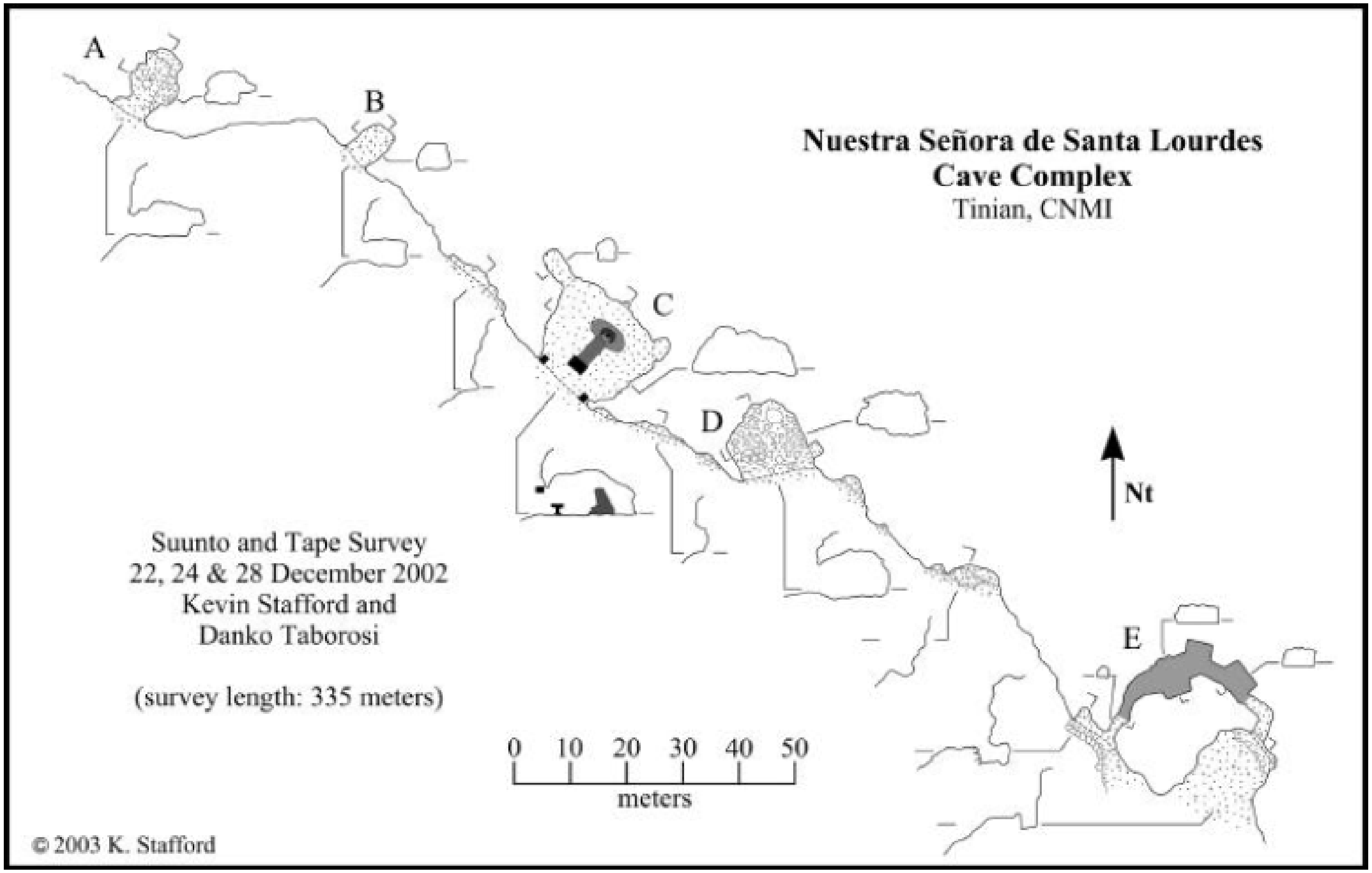

Figure 296: Map of Nuestra Señora de Santa Lourdes Cave Complex.

Orange Cave

Orange Cave is located 700 meters west/southwest of *Puntan Diapblo* in the Mariana Limestone (QTmu). This breached, flank margin cave has an entrance 14 meters wide and extends inland 16 meters with an average ceiling height of 3 meters. The cove is a single chamber that has been severely impacted by intense storm events, creating a floor covered in well-worn breakdown blocks and cobbles.

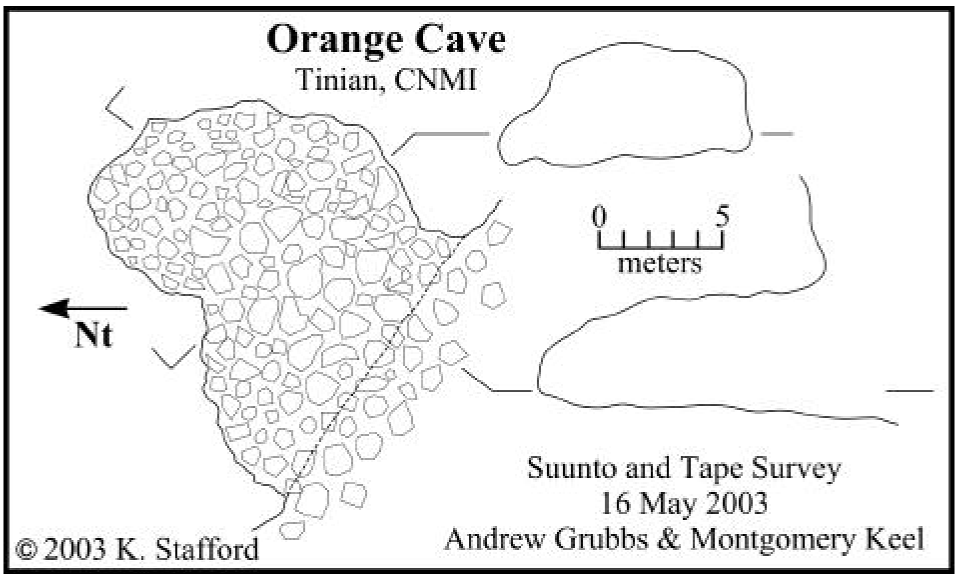

Figure 297: Map of Orange Cave

Pebble Cave

Pebble Cave is located 700 meters southeast of *Puntan Atgidon* in the Mariana Limestone (QTmu). It is a flank margin cave remnant located less than 1 meter above sea level in the northeastern portion of a large cove referred to locally as *Mendiola* Cove after the landowner. The entrance of the cave is 22 meters wide and 7 meters tall, with the cave extending inland 9 meters. The cave is floored with carbonate sand and pebble size carbonate clasts, in addition to several large breakdown blocks, which appear to be remnants of the collapsed ceiling located in the southern part of the cave.

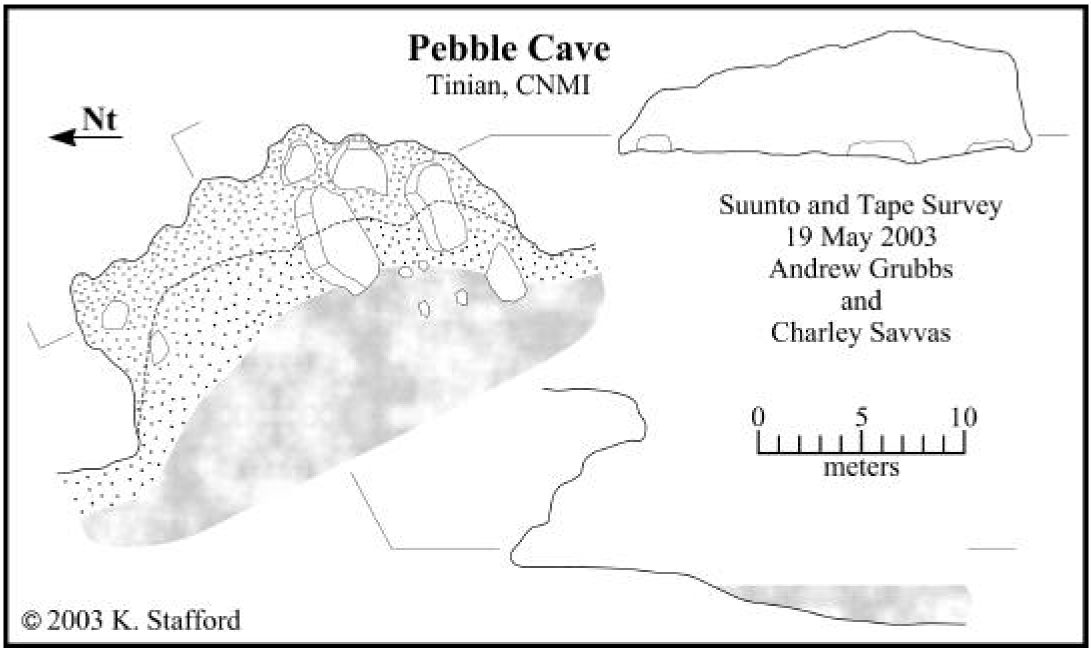

Figure 298: Map of Pebble Cave

Red Snapper Cave

Red Snapper Cave is located 900 meters south of *Puntan Lamanibot Sampapa* at the top of the coastal scarp in the Mariana Limestone (QTmu). It is a collapsed, flank margin cave remnant similar to the coves seen near *Unai Dangkolo*, except that it is 10 meters above sea level without a carbonate sand floor. The feature is divided by a large bedrock remnant on the coastal scarp side, which forms two collapsed entrances 11 and 16 meters wide. The feature extends inland 43 meters, decreasing in depth inland but averaging 4 meters. The most inland 5 meters remains roofed, as do several smaller regions on the periphery of the feature where bedrock pillars provided additional support for the roof. Several small terraces subdivide the feature, while the floor is primarily composed of bedrock with scattered breakdown blocks that appear to be remnants of the original roof. Speleothem deposits, including flowstone, stalactites, and stalagmites are seen throughout, but are more abundant in the areas that still retain protective ceiling remnants. The feature, although located well above mean sea level, appears to have been heavily impacted by numerous intense storm events and is primarily devoid of vegetation.

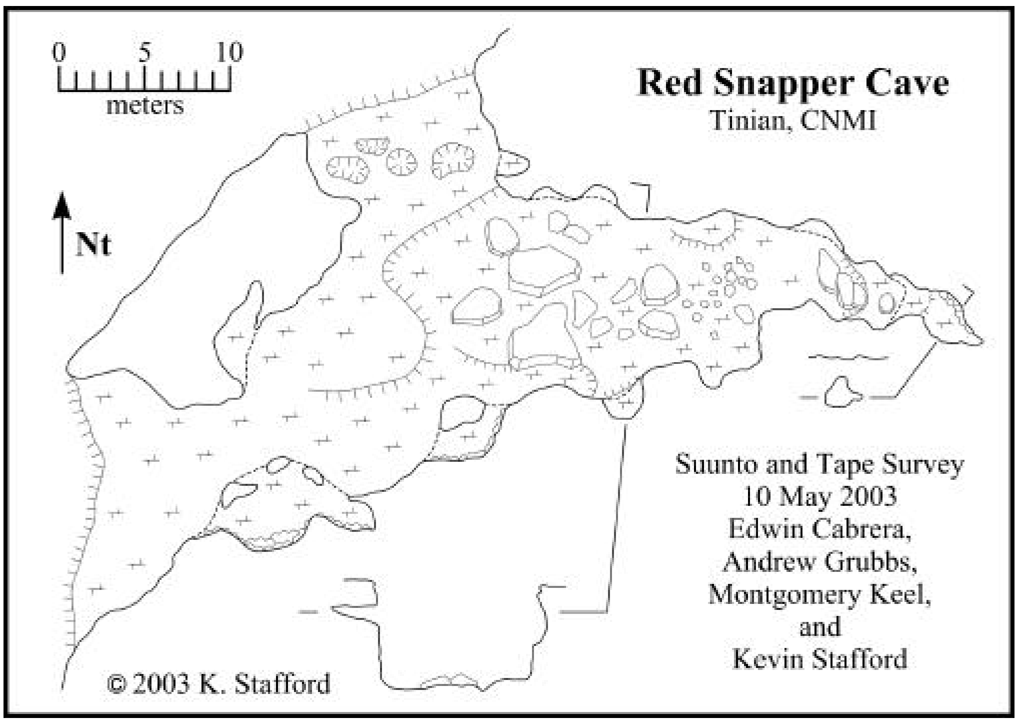

Figure 299: Map of Red Snapper Cave

Rock Hammer Cave

Rock Hammer Cave is a flank margin cave located 900 meters southeast of *Puntan Atgidon* in the Mariana Formation (QTmu). It is positioned 1 meter above mean sea level at a prominent headland in the cove locally referred to as *Mendiola* Cove after the landowner. The cave is breached at three locations, with one entrance submerged below sea level. The most prominent entrance is 2 meters wide and trends inland as a single chamber for 5 meters, where it is connected to the main cave chamber by a small, 20-centimeter wide passage. The main chamber has two entrances; the western entrance is located 1 meter below sea level and was not entered because of strong surf conditions, while the second entrance is located between the sumped entrance and the prominent entrance. This second entrance was partially blocked at the time of discovery, but with minor removal of bedrock, it was enlarged to allow entry through a 40-centimeter tall crawlway. The crawlway opens less than 1 meter inland into a 2-meter tall passage, which extends east for 10 meters connecting to the prominent entrance chamber. The west side of the main chamber drops below sea-level near-vertically into a pool of water 5 meters long and 2 meters wide. The entire feature is primarily retains a bedrock floor, excluding some breakdown blocks. Few speleothem deposits were seen in the cave, but the cave is a good example of how flank margin cave chambers that barely connected to each other and the surface.

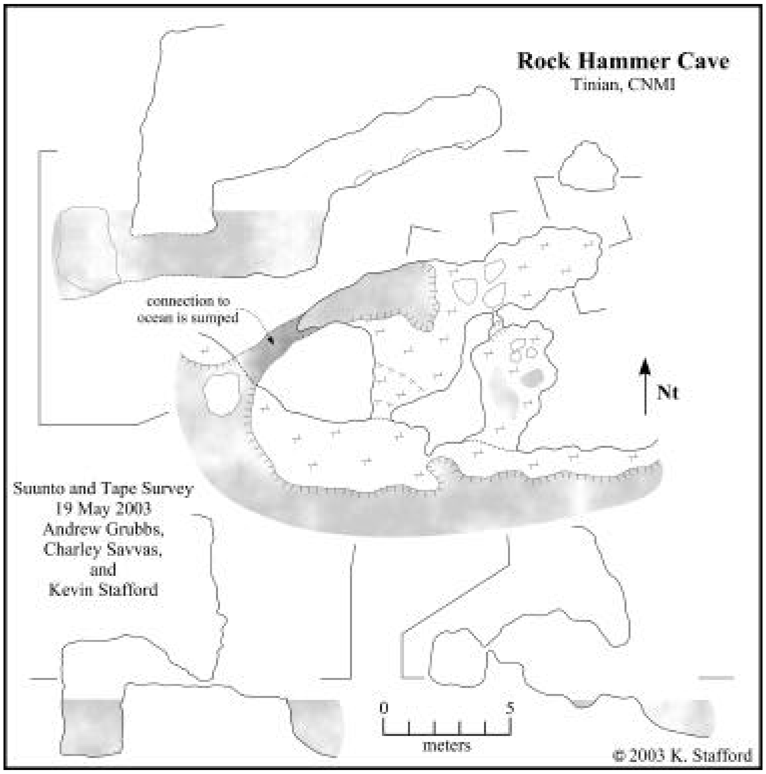

Figure 300: Map of Rock Hammer Cave

South Mendiola Cave

South *Mendiola* Cave is located 1200 meters north of *Puntan Diapblo* at the southern end of a large cove referred to as *Mendiola* Cove after the landowner. The cave is a large, flank margin cave developed in the Mariana Limestone (QTmcc) at sea level. The cave has an entrance 40 meters wide and extends inland 48 meters with an average ceiling height of 8 meters. In the central part of the cave, there is a 10-meter diameter skylight entrance exists, while along the northern edge of the chamber a second entrance connects to the ocean below sea level. The cave is bedrock floored with numerous large and medium size breakdown blocks covering large areas of the floor.

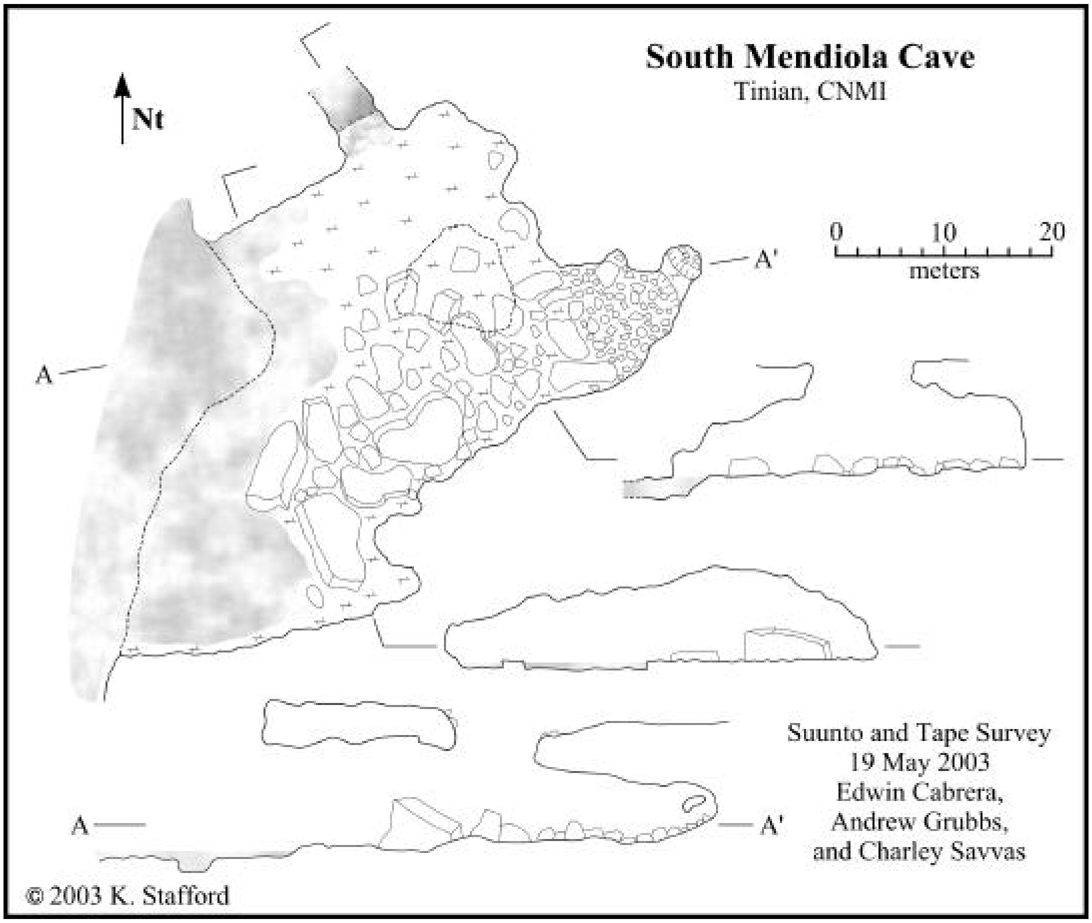

Figure 301: Map of South Mendiola Cave

Recharge Features

West Lasu Depression Cave

West *Lasu* Depression Cave is a closed depression recharge, located 1500 meters northwest of the peak of Mount *Lasu* in the Mariana Limestone (QTmu). The feature is approximately 25 meters in diameter and 4 meters deep, with the northern 5 meters of the feature covered by a 3-meter tall ceiling. The feature appears to be a significant recharge point with water being concentrated into the depression from the southwest edge. Lack of sediment coating the walls indicate that water does not pond here and enters the subsurface as diffuse flow, but that it acts as a fast flow route. This feature represents the most significant recharge feature that has be located northwest of Mount *Lasu*.

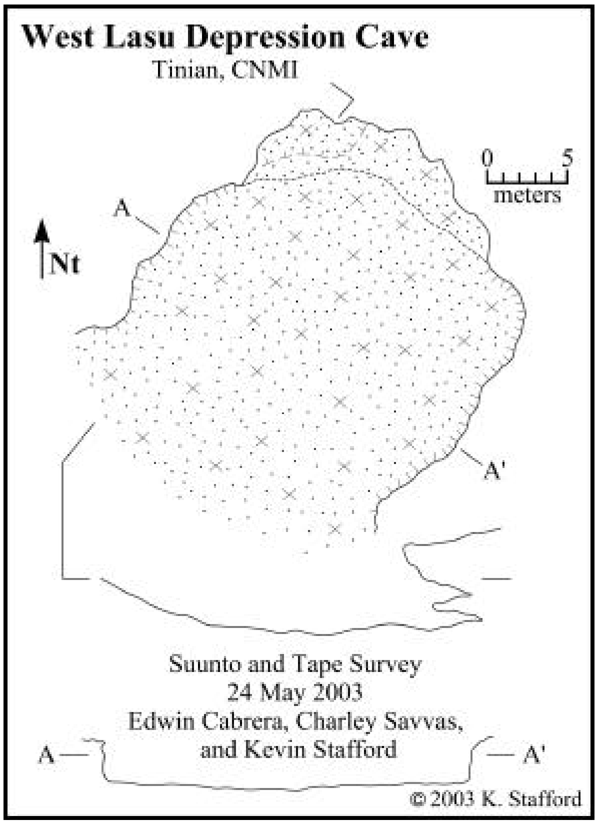

Figure 302: Map of West Lasu Depression Cave

MEDIAN VALLEY

Banana Holes

CUC Cave

CUC Cave is a banana hole type cave located 500 meters east of the CUC power plant. It consists of a low broad chamber 8 by 9 meters with an average ceiling height of 1 meter. The cave contains numerous speleothem deposits primarily as stalactites and one 0.5-meter diameter column located in the middle of the feature. The floor is primarily alluvium introduced from two breached entrances; a small entrance located in the northwest corner of the feature and a larger, main entrance located in the northeast corner. The cave is located in dense vegetation on relatively flat land and is easily overlooked; however, the cave does show evidence of human modification including many broken cave formations.

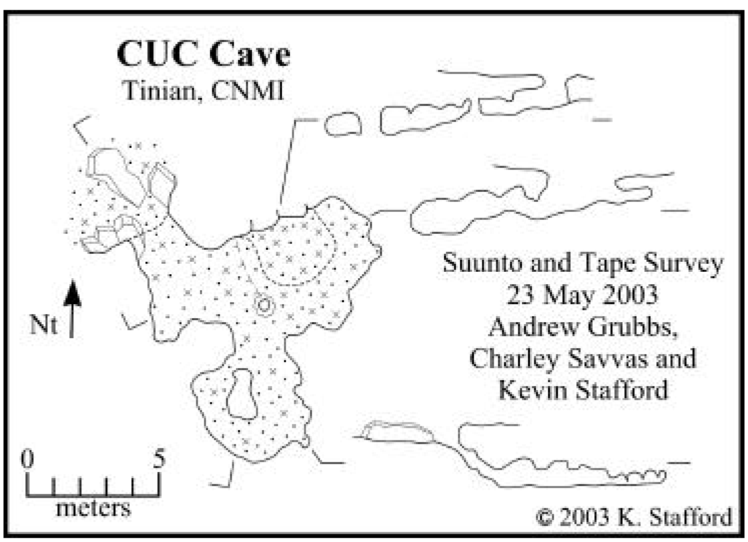

Figure 303: Map of CUC Cave

Discharge Features

Gecko Cave

Gecko Cave is located approximately 200 meters southeast of *Unai Masalok* on the coastline at sea level. It is developed in the Mariana Limestone (QTmu) and discharges freshwater through a tubular passage. It is developed along a dissolutionally enhanced joint oriented at approximately 60^{o}, which extends inland for more than 20 meters from a small coastal bay. Directly south of Gecko Cave is another feature that extends inland a similar distance, but is mostly water-filled, such that during exploration it could not be surveyed because of strong surf conditions. A freshwater discharge rate could not be calculated within in the cave for similar reasons, but significant fresh water could be observed mixing with saltwater inside the cave.

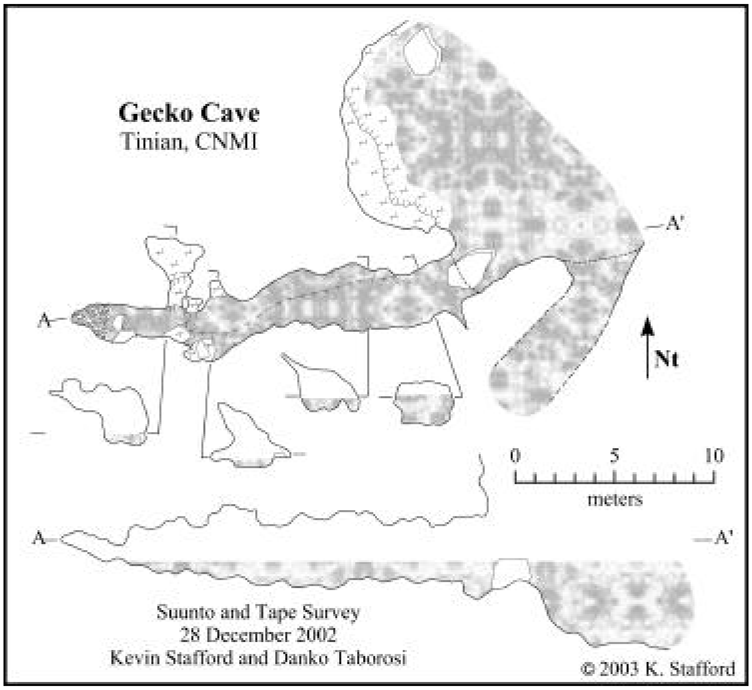

Figure 304: Map of Gecko Cave

Leprosy Discharge Feature

The Leprosy Discharge Feature is located near the "Historic Leprosarium Site" in the Mariana Limestone (QTmu). The feature is approximately 25 meters long, 7 meters wide, and 2 meters deep. The feature has two small natural bridges located in the eastern portion where weathering of dipping foreshore deposits has eroded out beds preferentially. Along the walls of the feature that are in contact with ocean water, there are small-scale dissolutional features that appear to represent mixing dissolution from discharging freshwater. Minor mixing of fresh water was observed, but due to strong surf conditions, no significant salinity variations could be detected.

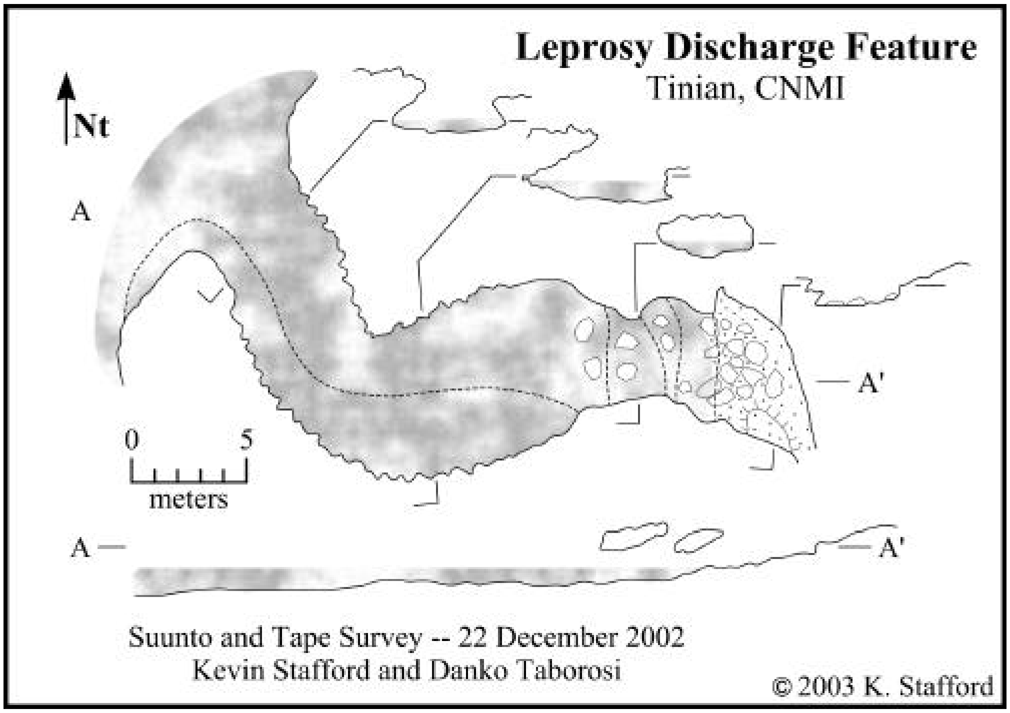

Figure 305: Map of Leprosy Discharge Feature

Fissure Caves

Dripping Tree Fracture Cave

Dripping Tree Fracture Cave, developed in the Mariana Limestone (QTmca), is located approximately 200 meters south of *Unai Dangkolo* and consists of a long fracture oriented approximately 335°. The feature was mapped for almost 300 meters with several small fractures intersecting it at high angles. The majority of the feature is unroofed, but two sections, each approximately 20 meters long, have roofs composed of large breakdown blocks. The feature has been formed by solutional modifications of a bank-margin failure crack. It is up to 5 meters wide and greater than 16 meters deep, with depth varying greatly depending on the amount of breakdown and alluvium present. Throughout the feature, speleothems are present, with larger accumulations present in the roofed portions. At the deepest part of the feature, the southern end, there is a segment containing 1.5-meter deep brackish water. Although no direct connection was discovered to the ocean in this part of the feature, the presence of marine fauna indicates there must be some connection. In the northern portion of the feature, where it connects directly to the ocean, a Japanese pillbox was constructed approximately 6 meters above sea level.

Immediately inland from Dripping Tree, there are several smaller fractures that are not humanly accessible. They are formed parallel to the main fracture, resulting from the inland migration of cliff margin retreat. These features show less dissolutional enhancement than that seen in Dripping Tree Fracture Cave.

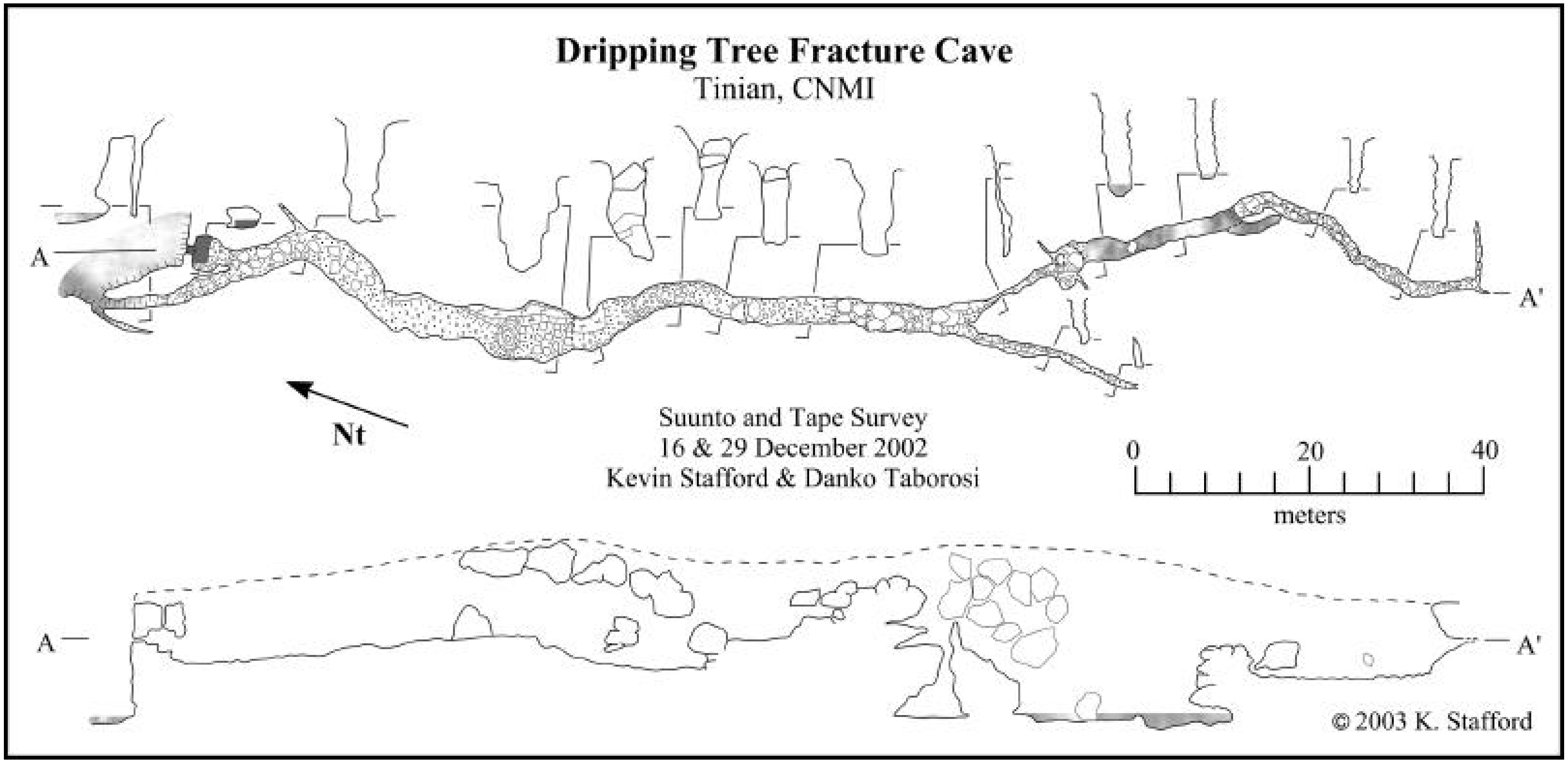

Figure 306: Map of Dripping Tree Fracture Cave.

Flank Margin Caves

Andyland Cave

Andyland Cave extends 20 meters inland from the northwest corner of *Unai Dangkolo* and is developed in the Mariana Limestone (QTmca). It is a flank margin cave consisting of one primary chamber with a maximum height of 3.5 meters and a width of 8 meters. The floor is composed of carbonate beach sand, which may be infilling additional cave passage in the western portions. Andyland Cave is positioned in-line with the northern scarp of *Unai Dangkolo* and *Liyang Dangkolo*, with a 10-meter gap separating Andyland Cave from *Liyang Dangkolo*. Based on carbonate sand observed in eastern portion of *Liyang Dangkolo*, it is likely that the two caves physically connect but are currently separated by sand accumulation.

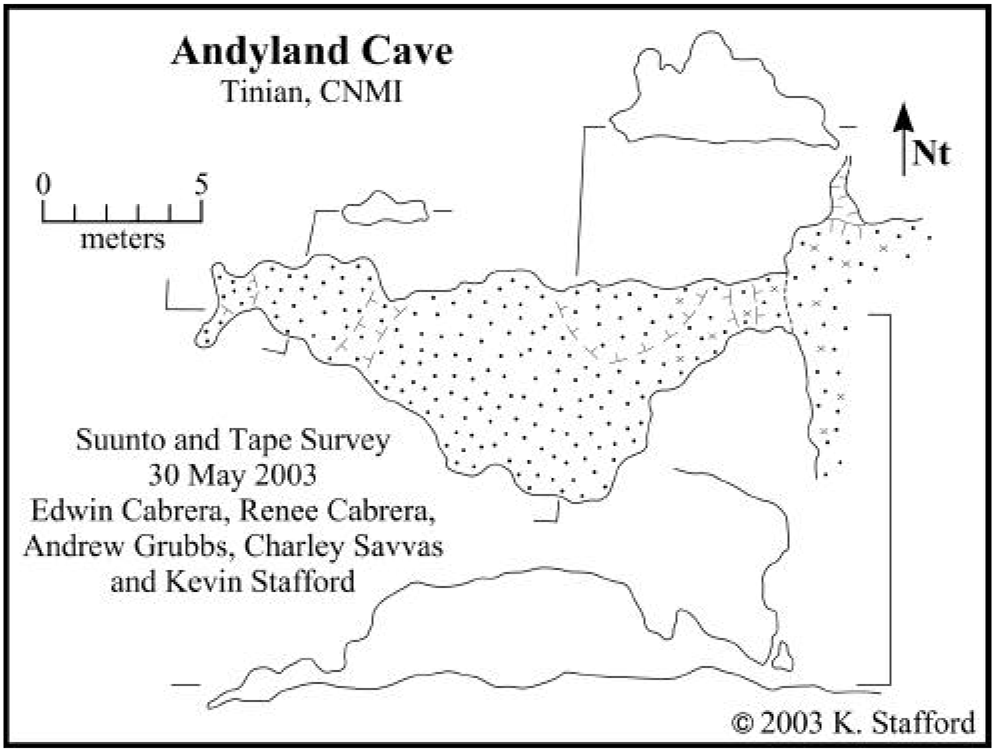

Figure 307: Map of Andyland Cave

Barcinas East Cave

Barcinas East Cave is a flank margin cave located approximately 200 meters east of *Barcinas* West Cave on the north side of *Barcinas* Cove (Turtle Cove) in the Mariana Limestone (QTmu). It is positioned approximately 1 meter above mean sea level with a width of 34 meters, depth of 18 meters and maximum ceiling height of 4 meters. The main cave is separated by 3 bedrock pillars and is influenced by two joints trending north/northeast. The interior of the main cave is devoid of speleothems and appears to have been severely impacted by intense storm events, producing a flat bedrock floor that is near level with high tide levels. A few meters west of the main cave, a smaller flank margin remnant exists that is partially protected by the rock comprising the main cave, which extends slightly farther seaward.

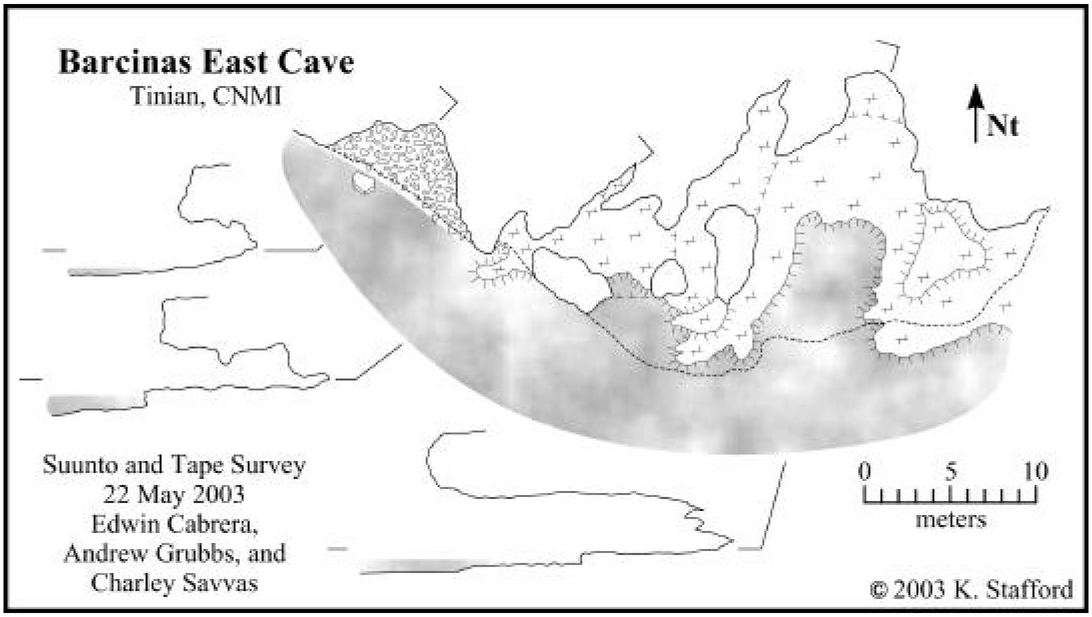

Figure 308: Map of Barcinas East Cave

Barcinas West Cave

Barcinas West Cave is a flank margin cave located approximately 200 meters west of *Barcinas* East Cave on the north side of *Barcinas* Cove (Turtle Cove) in the Mariana Limestone (QTmu). It is a single chamber positioned approximately 1 meter above mean sea level with a width of 22 meters, depth of 15 meters, and maximum ceiling height of 5 meters. A single small column divides the entrance in half, although a large breakdown block in the western portion of entrance gives the appearance of dividing the cave into three entrances. The cave is partially protected from the direct impact of waves by a large resistant bedrock pillar is located approximately 6 meters south of the entrance. Extending 5 meters to the east of the cave is a small passage that is developed along a joint. The cave is devoid of speleothems and the floor is covered with large breakdown blocks and cobbles that have been well rounded by wave action.

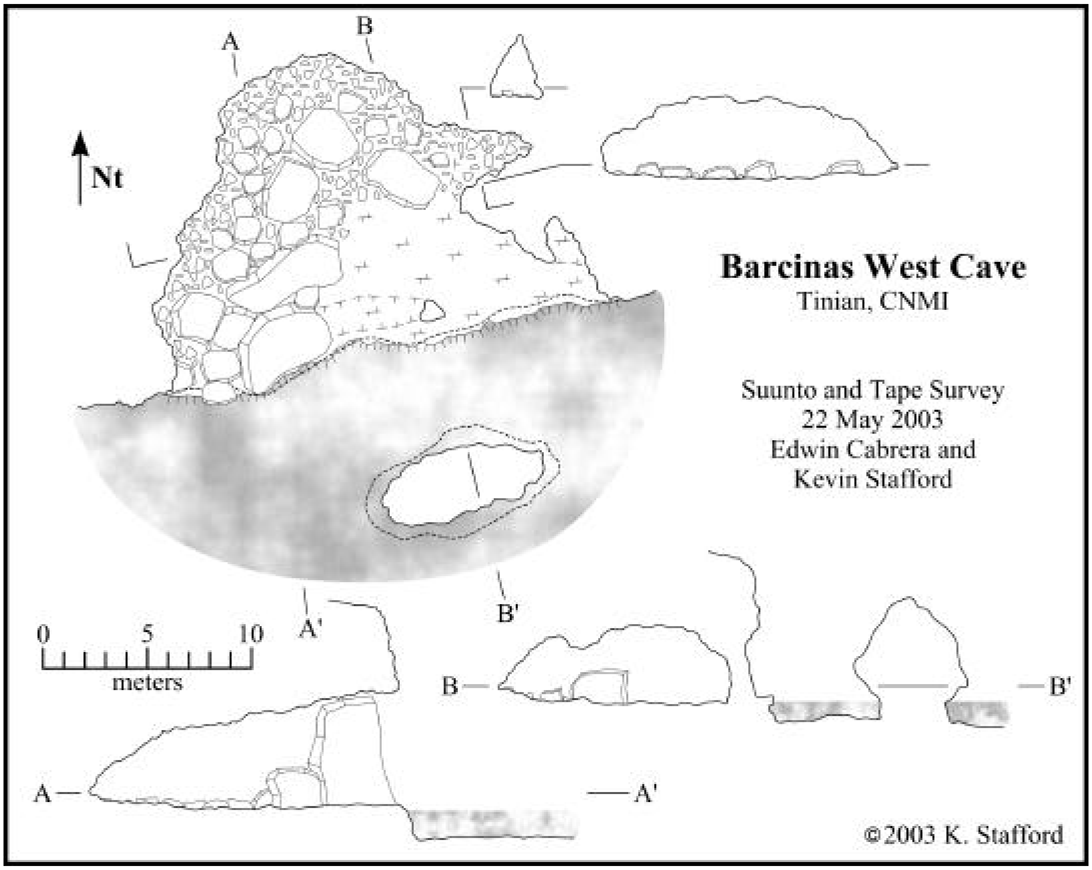

Figure 309: Map of Barcinas West Cave

Dynasty Cave

Dynasty Cave is a breached flank margin cave located 100 meters north of Taga Beach in the Mariana Limestone (QTmu). The cave is 12 meters wide at the entrance and extends inland 15 meters with an entrance ceiling height of 3 meters. The majority of the cave floor is slightly below sea level, while the inland portions consist of a bedrock ledge 2 meters above the main floor. Several large breakdown blocks are located in the entrance area and appear to be pieces of the original roof. These breakdown blocks originally extended further seaward but have now been transported slightly inland by intense wave action.

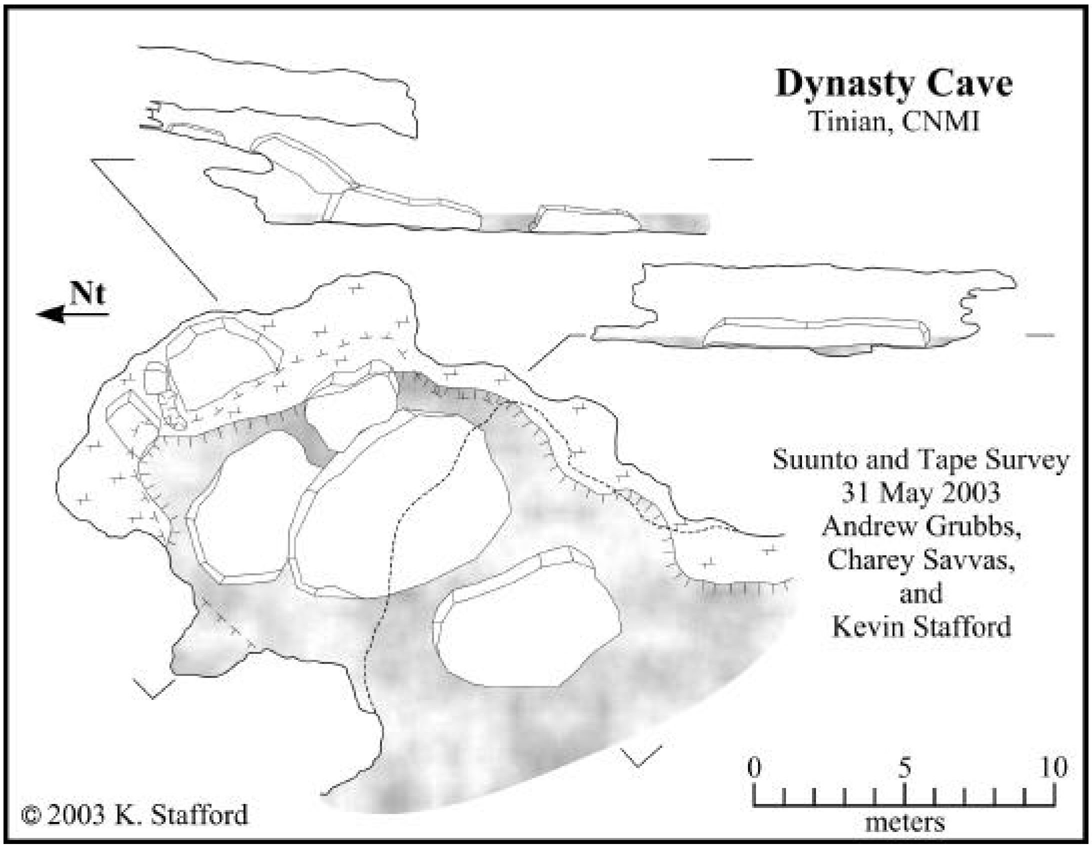

Figure 310: Map of Dynasty Cave

Hidden Beach Cave

Hidden Beach is located at *Unai* Asiga, 1000 meters north of *Unai Dangkolo*, on the east coast. It is developed in the Mariana Limestone (QTmca) and extends inland 80 meters with an average width of 11 meters, but the majority of the ceiling is absent. The entrance is located at sea level and has a carbonate sand floor sloping gently inland. The cave has several small passages that extend from the north and south sides of this east/west trending feature, but they all terminate within 5 meters. The ceiling is present 27 meters inland, where it forms a 5-meter wide arch across the cave, before the ceiling is breached by a large collapse measuring 20 meters by 7 meters that connects to the surface, leaving less than 5 meters of ceiling width around the periphery of the large skylight entrance. Farther inland the ceiling remains intact for the remainder of the cave except for the most inland portions, which is breached and connects to the land surface. Minor speleothems are seen throughout the cave and one significant side passage is present in the southeast corner of the feature near the seaward entrance. This passage is located 3 meters above the floor on the cave wall and forms a looped passage over 10 meters long, averaging 2 meters in height and width. This significant feature not only represents one of the larger caves on Tinian, but it well represents an intermediate stage in the transition from flank margin caves to coves that are seen on Tinian. The coves located farther south at *Unai Masalok* and *Unai Dangkolo* have experienced greater erosion from coastal process, while more intact caves like *Liyang Dangkolo* show limited breaching primarily by ceiling collapse. Therefore, Hidden Beach Cave shows the transition stages in coastal erosion from complete flank margin caves to coves on carbonate islands.

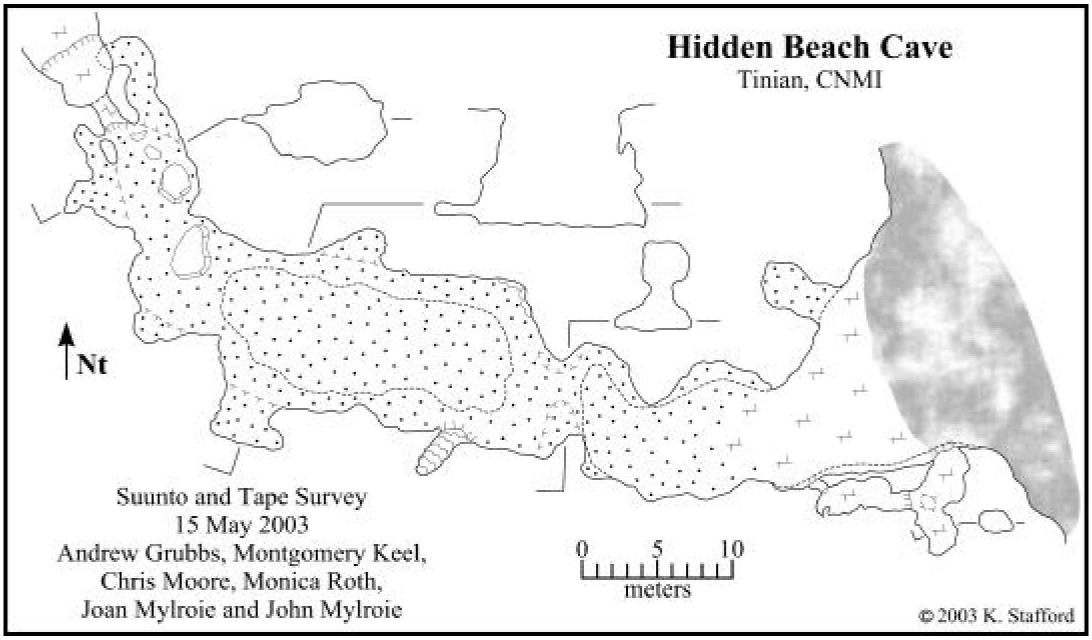

Figure 311: Map of Hidden Beach Cave

John's Small Cave

The entrance to John's Small Cave is located approximately 200 meters west of the *Unai Dangkolo* and is developed in the Mariana Limestone (QTmca). This FM cave is oriented roughly north by northeast with a length of 35 meters, width of 15 meters and depth of 12 meters. The entrance area is a complex collapse composed of numerous blocks and sediment. The southern portion of the cave exhibits less collapse, but has extensive speleothems and alluvium derived from sources to the south, in the direction of the small, unsurveyed passage at the far southern end of the cave. Throughout the cave, the original dissolutional morphology can be seen, but in most locations it is obscured by collapse or overprinted by speleothems. This cave and *Liyang Dangkolo* are approximately 20 meters apart in the subsurface, based on a surface survey that connects them.

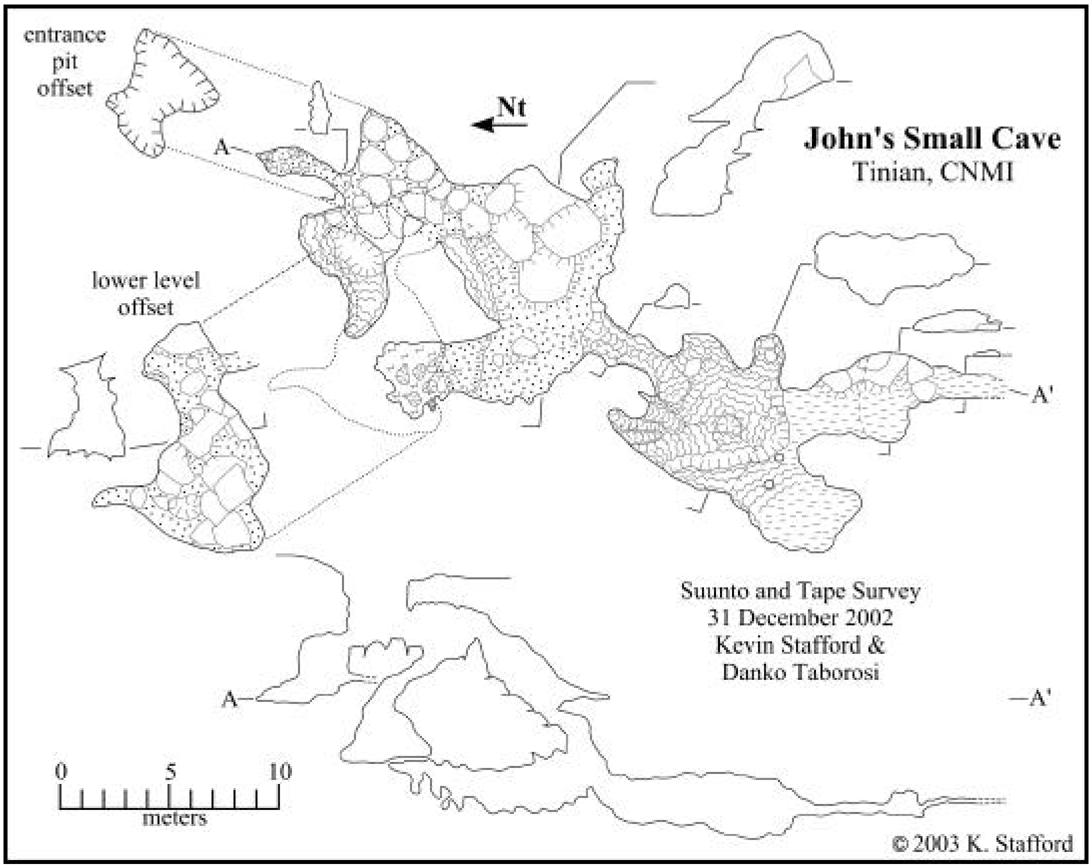

Figure 312: Map of John's Small Cave

Leprosy Caves

The Leprosy Caves are breached, flank margin caves developed in dipping foreshore deposits in the Mariana Limestone (QTmu) on the coastline, approximately 200 meters south of the historic Leprosarium site. The site consists of series of three small caves and two large caves along a section of coast 120 meters long. The two large caves measure roughly 16 meters by 20 meters each with maximum ceiling heights of 8 meters. A ceiling breach on the inland side has created a second entrance to the southern large cave. The caves contain bedrock floors with some breakdown and carbonate sand near the entrances, but are devoid of speleothems. These caves all show evidence of being impacted by intense surf, which may explain the complete absence of speleothems.

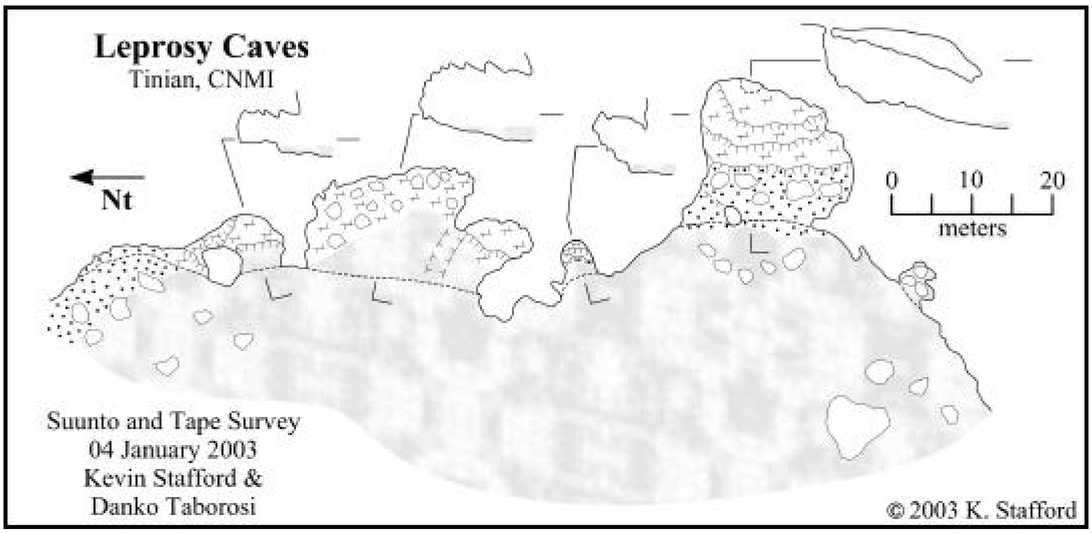

Figure 313: Map of Leprosy Cave

Liyang Dangkolo

Liyang Dangkolo, also known as Long Beach Cave, the largest cave on Tinian, is approximately 100 meters inland from Long Beach (*Unai Dangkolo*). It is developed in the Mariana Limestone (QTmca) and measures approximately 35 meters by 70 meters with a central main chamber that extends to 16 meters depth. The cave contains several large bedrock pillars that separate areas and numerous smaller passages extending off of the main chamber in all directions. The cave appears to be predominantly intact with four entrances located in the ceiling of the main chamber, requiring a vertical descent to enter to the cave. In various areas of the cave, speleothems are extensive, while the main chamber floor is composed of breakdown talus created by the collapse of the ceiling. In the far eastern part of the cave, there is a large amount of carbonate sand, which may indicate a second breached entrance, possibly Andyland Cave. Through the center of the cave, a dissolutionally enhanced, north/south trending fracture is present that is associated with the largest collapse entrance. This large cave represents archetypical flank margin cave development for the Island of Tinian. Throughout the cave, minor human modifications have been made including the construction of a stacked rock wall in the east central area.

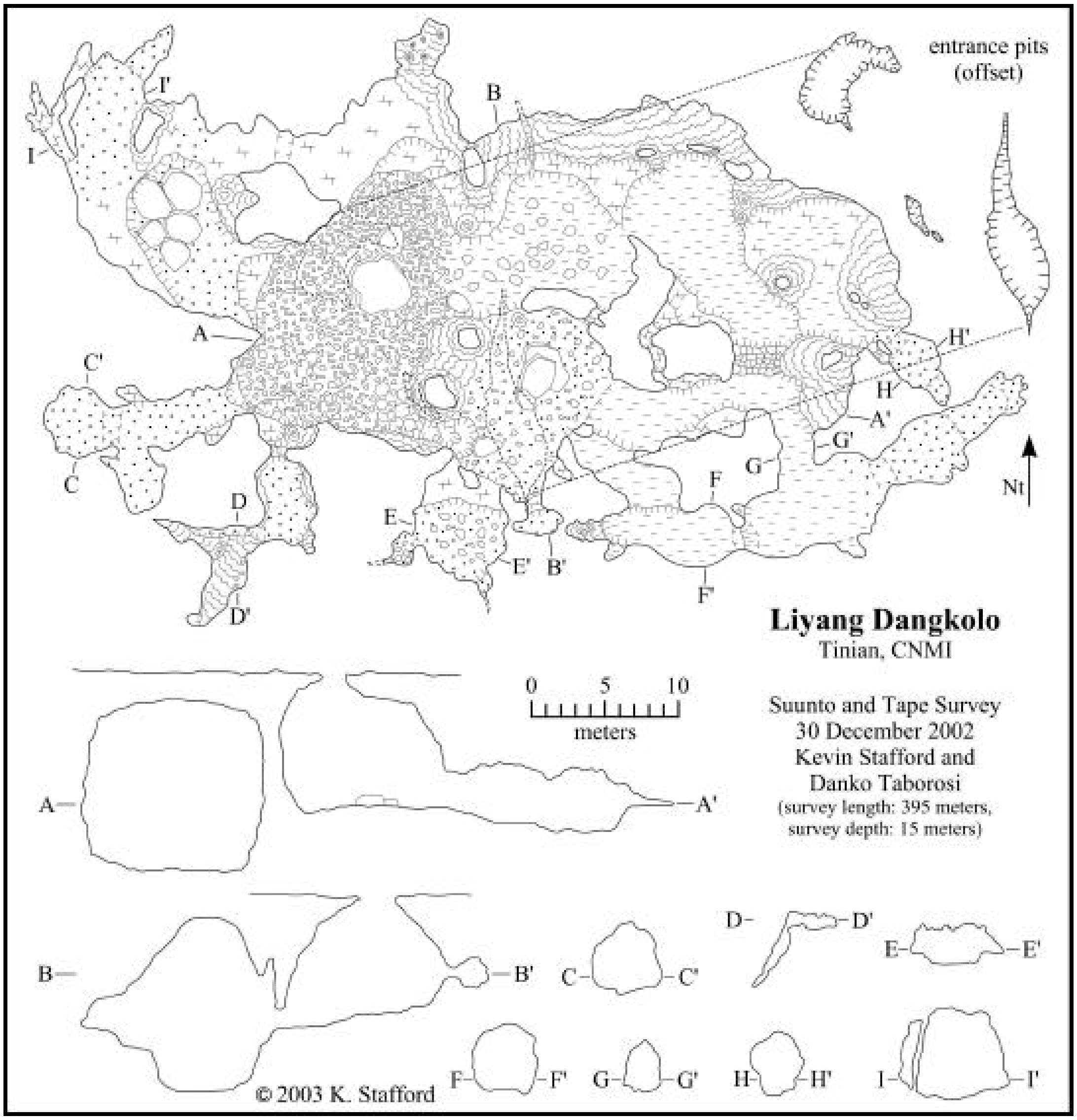

Figure 314: Map of Liyang Dangkolo

Metal Spike Cave Complex

The Metal Spike Cave Complex is located approximately 500 meters inland from *Unai Dangkolo*, oriented northeast, approximately 10 meters west of the road to the same region. This feature consists of a series of collapsed flank margin caves in the Mariana Limestone (QTmca) with a few remaining chambers. It appears that the entire feature was connected in the past, but due to cliff retreat and collapse it is now disjointed. When connected, this feature would have been more than 130 meters long.

The southwestern part contains the largest collapsed chamber, which is approximately 12 meters in diameter and 2 meters deep, indicating that a large void collapsed at depth to create this surface expression. To the south of this collapse feature is a small roofed chamber approximately 5 meters by 6 meters with a 2-meter tall ceiling. To the west of the large collapse feature is a large section of remnant flank margin cave that is developed along and partially under the western edge of the collapse. This chamber extends to a depth of 8 meters and contains speleothems throughout, including large columns in the entrance area.

Northeast of the large collapse feature is a 30 meter section of 5 meter high cliff wall, that has several small solutional chambers with speleothems located in and around them. This appears to be the remnants of the inland wall of flank margin cave development that has been almost completely removed by cliff retreat.

Continuing northeast across a 15-meter section of large angular limestone blocks, a second collapsed feature is present. This feature is approximately 5 meters by 10 meters with parts of the original roof remaining. Extending off the northeast corner of this second collapse feature is a small passage extends for an additional 8 meters, which contains speleothems and additional breakdown.

In the northeastern part of the cave complex is a series of partially breached chambers that extend are connected for approximately 40 meters with widths ranging from 4 to 8 meters and a maximum ceiling height of 5 meters. The southwestern portion of this region is a ceiling collapse entrance approximately 5 meters by 10 meters, with roofed chambers extending to the east and south. The far northeastern part consists of a 25-meter long passage that terminates in a 4 meter by 6-meter chamber with speleothems. This chamber is under the road to *Unai Dangkolo*. In the middle part of this passage, a pit entrance, which is approximately 1.5 meters in diameter, breaches the surface.

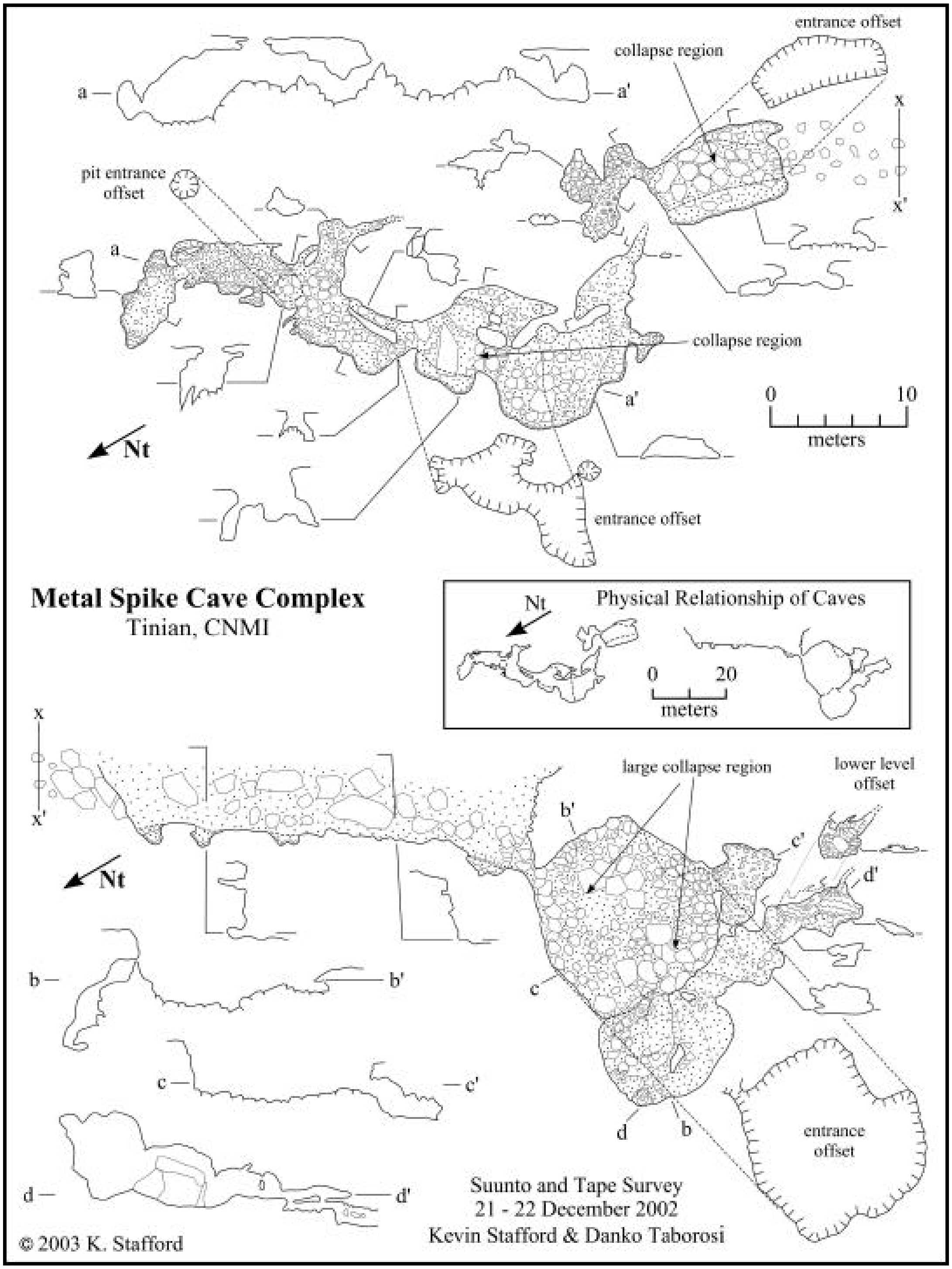

Figure 315: Map of Metal Spike Cave Complex

North Unai Dangkolo

North *Unai Dangkolo* is the northern scarp of *Unai Dangkolo* and the two coves north of it. It is developed in the Mariana Limestone (QTmca) and covers 300 meters of coastline. The northern most cove has a width of 50 meters and extends inland 20 meters with ceiling remnants extending from the wall less than 5 meters for the majority of the cove, which is floored with carbonate sand. The main cove at North *Unai Dangkolo* has a seaward width of 85 meters and extends inland 95 meters with the width decreasing to 25 meters at a distance of 35 meters inland. Small regions are roofed near the cove walls and minor amounts of well-weathered flowstone can be seen in places. The entire cove is floored with carbonate sand with several large collapse blocks located on the north and south side of cove near the shoreline. Several prominent fractures are dissolutionally widened throughout the cove and a 15-meter long, 3-meter wide, 1-meter tall pillbox is constructed in the northeast corner of the cove. The northern scarp of *Unai Dangkolo* is 90 meters south of this large cove and extends inland 60 meters before it turns south into dense vegetation, which prevented a continuation of the survey along the perimeter of *Unai Dangkolo*. However, Andyland cave was located at this southward bend in the cove. The majority of North *Unai Dangkolo* is floored with carbonate sand, but dense vegetation grows in the regions that are farther inland and more protected from normal coastal processes.

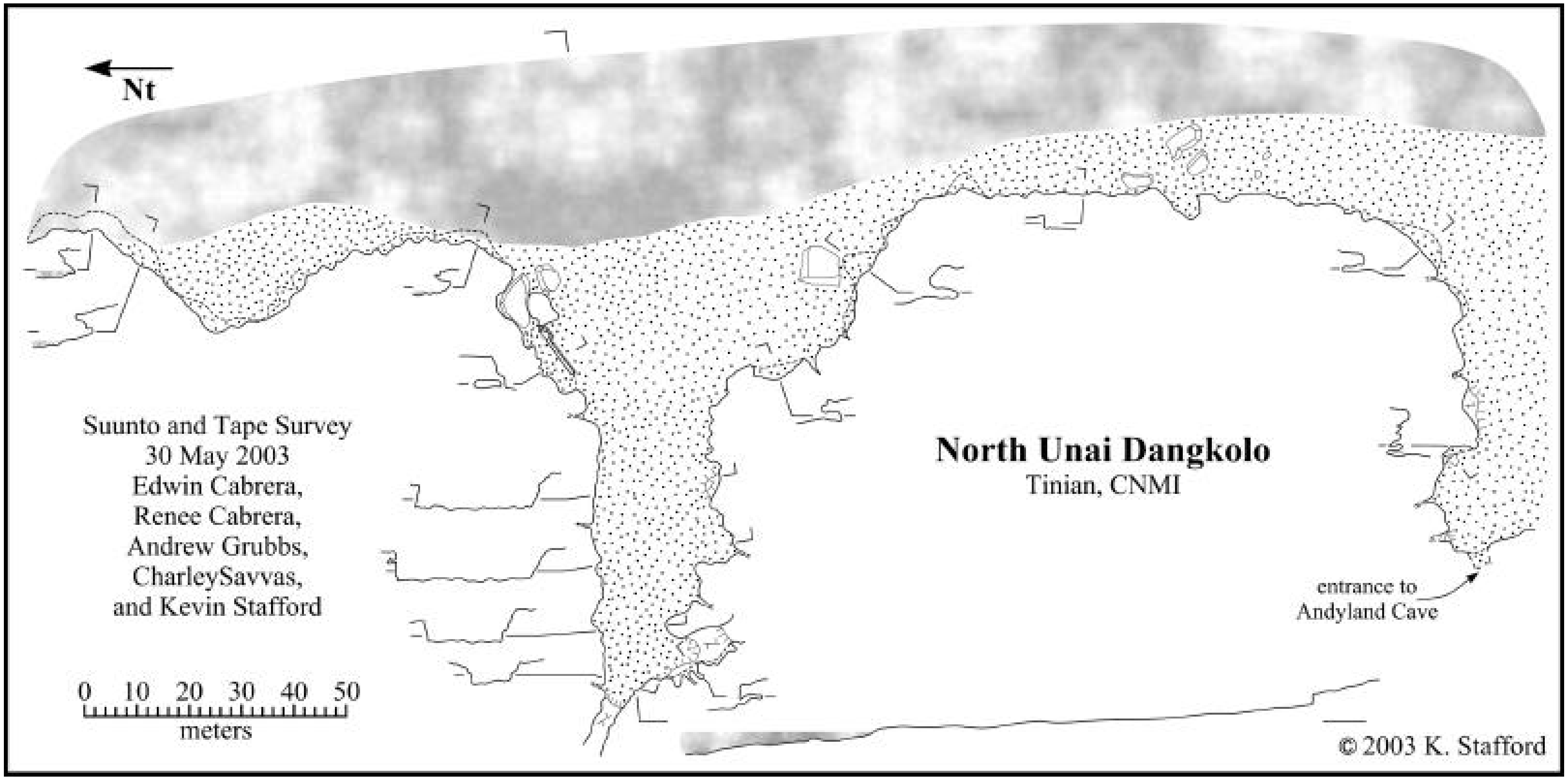

Figure 316: Map of North Unai Dangkolo.

South Unai Dangkolo

South *Unai Dangkolo* is a large pocket beach developed in the Mariana Limestone (QTmca) just south of *Unai Dangkolo* and developed in the Mariana Limestone (QTmca). The feature is 20 meters by 40 meters and contains some small remnant cave chambers and speleothems, which indicate that this was originally a large flank margin chamber that has been breached by coastal processes including the removal of the majority of the roof. A small dissolutionally enhanced fracture connects this feature to *Unai Dangkolo* to the north, while a less developed extension of this same fracture extends to the south from the feature in the direction of Dripping Tree Fracture Cave. Although not surveyed during fieldwork, *Unai Dangkolo*, to the north, appears to have a similar flank margin cave origin, but is much larger and has been more extensively eroded by coastal processes.

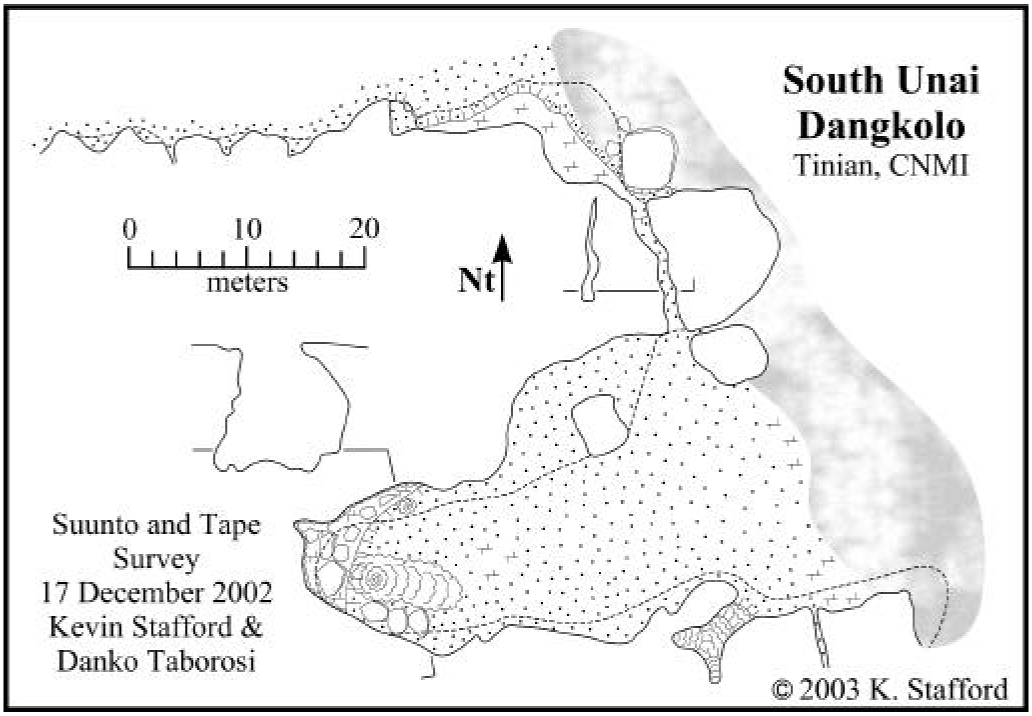

Figure 317: Map of South Unai Dangkolo

Swimming Hole Cave Complex

Swimming Hole Cave Complex is located 700 meters south of the historic Leprosarium site on the west coast. It consists of three flank margin cave remnants developed in the Mariana Limestone (QTmu). The northern cave in the complex forms a looped passage with two entrances; the larger, northern entrance is 10 meters wide and the smaller, southern entrance is 1.5 meters wide. The loop passage extends inland 8 meters with an average width of 2.5 meters and height of 1.5 meters. The middle cave in the complex also contains two entrances forming a looped passage, with the two entrances averaging 2 meters wide and extending inland 9 meters with and average width of 3 meters and height of 1.5 meters. The southwestern cave has a single 2-meter wide entrance and extends inland 12 meters, where it widens to 7 meters with a ceiling height of 1.5 meters. The caves in this complex have soil and detritus floors with some breakdown blocks located near the entrances. All three caves show evidence of human modification, primarily the leveling of floors.

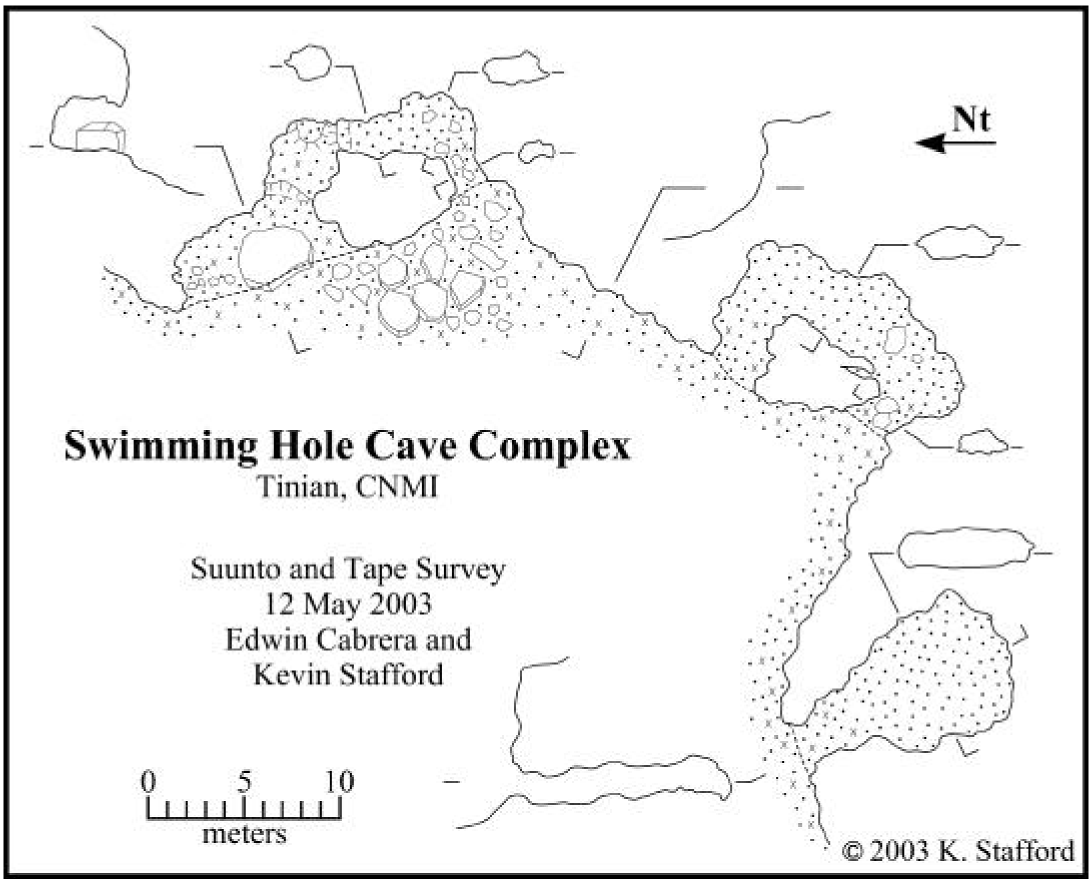

Figure 318: Map of Swimming Hole Cave Complex

Unai Masalok

Unai Masalok is a series of pocket beaches located on the east coast of the island and developed in the Mariana Limestone (QTmca). This series of four beaches is approximately 150 meters wide and extends inland for up to 50 meters. The individual beaches have several small remnant cave passages that extend inland from the cliff walls, remnant bedrock pillars, and speleothems. The overall morphology of the beaches and the presence of speleothems indicate that *Unai Masalok* was a series of flank margin caves that were breached by coastal processes and cliff retreat. Based on the available evidence, these features would have consisted of large flank margin cave chambers that were possibly connected where each of the individual pocket beaches are separated along the coastline. Throughout the feature there are numerous joints, which appear to be associated with cliff retreat. No evidence of offset could be discerned along these joints, but they appeared to trend roughly parallel to the coastline with variations in actual orientations throughout.

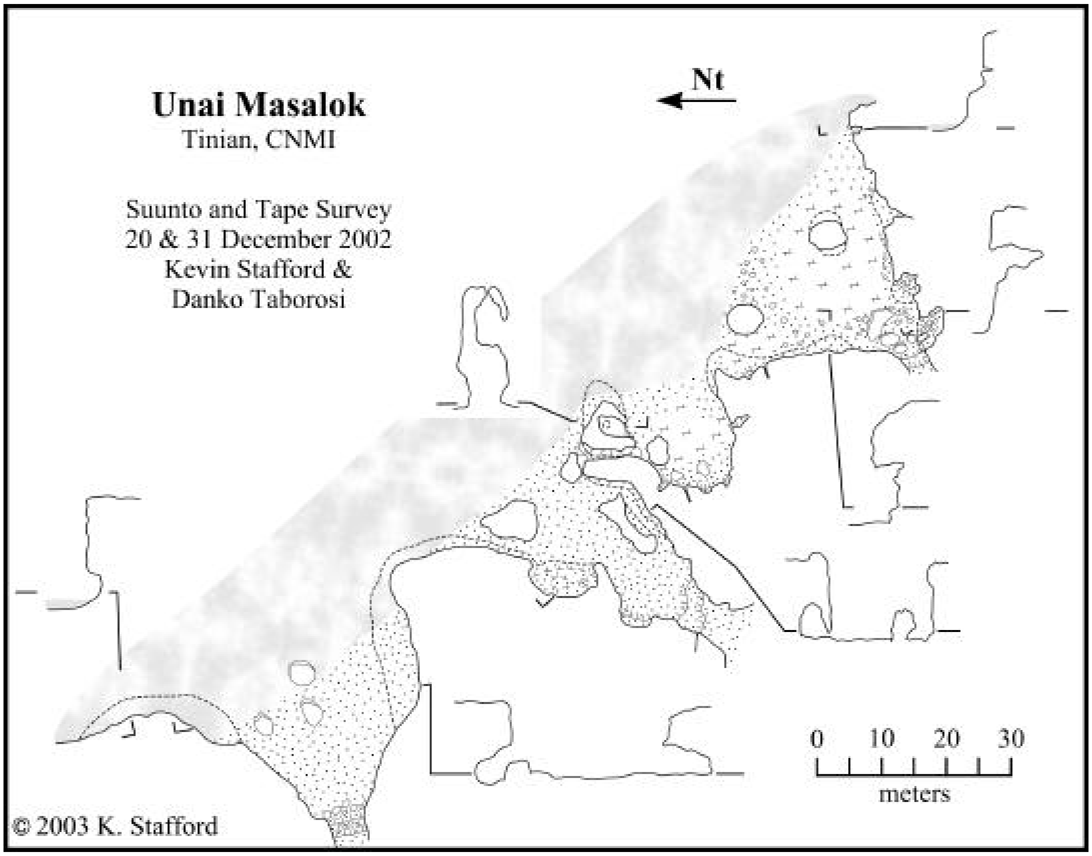

Figure 319: Map of Unai Masalok

Fracture Caves

Plunder Cave

Plunder Cave is located near the Water Cave, approximately 2 kilometers south of Taga Beach and 300 meters inland from the west coast. It is developed at the boundary between the Median Valley and the Southeastern Ridge provinces along a northeast/southwest trending fault that dips at approximately 35° to the southeast. This dissolutionally enlarged fracture cave is formed in the Mariana Limestone (QTmu) and is approximately 43 meters by 12 meters, extending to a depth of 13 meters. The cave consists primarily of one large chamber that contains extensive speleothems and much breakdown. In the central parts of the cave, a small, lower chamber is present in the breakdown blocks, where stacking of collapse material has created a larger void that is humanly passable. In the northern parts of the cave, large breakdown blocks have been covered by massive speleothem accumulations, but void space beneath these blocks has left a smaller passage. On the map, locations marked 1, 2, and 3 represent locations where geologic specimens were taken for future isotope analysis.

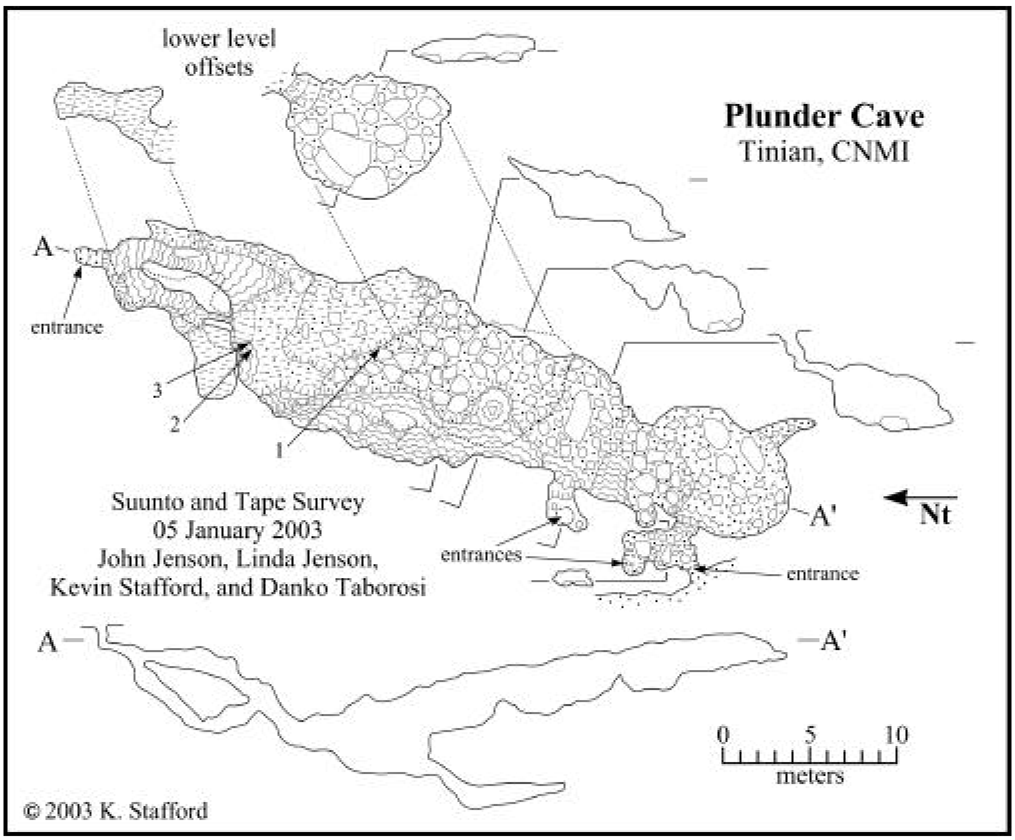

Figure 320: Map of Plunder Cave

Water Cave

The Water Cave is located near Plunder Cave, approximately 2000 meters south of Taga Beach and 300 meters inland from the west coast. It is developed at the boundary between the Median Valley and the Southeastern Ridge provinces along a northeast/southwest trending fault that dips at approximately 35^{o} to the southeast. This dissolutionally enlarged fracture cave is formed in the Mariana Limestone (QTmu) and is approximately 35 meters by 14 meters, descending to a depth of 13 meters where there is a 1-meter deep, linear pool of fresh water is encountered along the southern wall of the cave. The cave has extensive secondary deposits along in the central and northeastern parts, while the western parts are composed of much collapse material.

This feature shows evidence of extensive use by the Japanese military during World War II, probably because of the available water source in the bottom of the cave. There are anecdotal reports that the cave was sealed during the war on Tinian, which may explain the extensive breakdown and rubble in the western parts of the cave. However, the two entrances to the cave are small passages located in solid bedrock indicating that there was another entrance to this cave that is still blocked, if the reports are true.

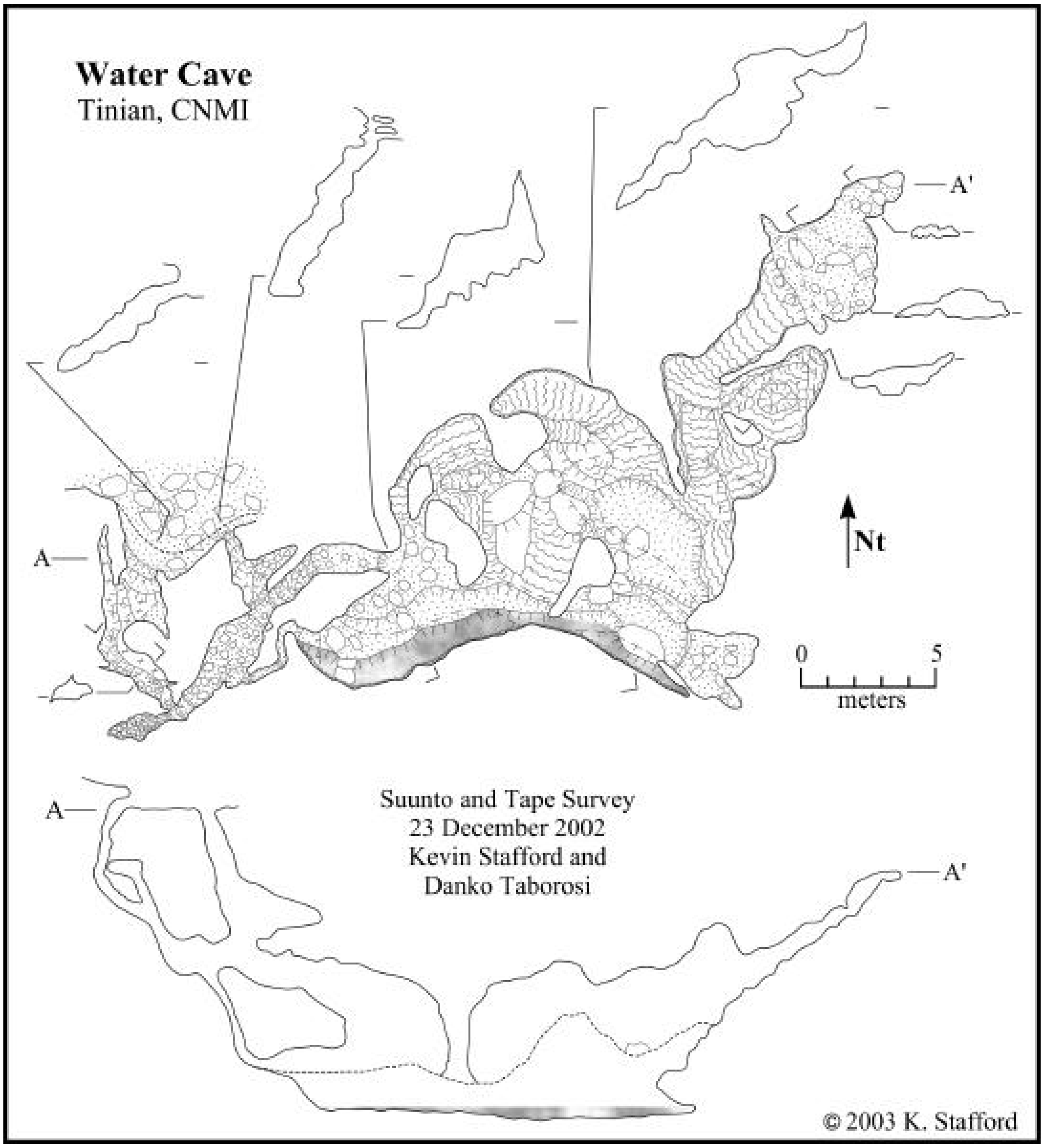

Figure 321: Map of Water Cave

NORTH-CENTRAL HIGHLAND

Banana Holes

Rootcicle Cave

Rootcicle cave is a collapsed banana hole feature that is developed in the Mariana Limestone (QTmca). This feature is located approximately 300 meters northeast of the Lasso Shrine at Mt. *Lasu* on a small terrace level above the Laderan Mangpang scarp. This feature has a central entrance formed by collapse and is elongated in a northwest/southeast direction, with dimensions of 10 meters by 33 meters. Through the long axis of the cave, there is a fault trending 120^{o}-130^{o} and dipping approximately 75^{o} to the southeast. The fault has dropped the southern portion of the cave by approximately 2 meters relative to the northern portions. This fault trend extends to the east as a low passage that is not humanly passable. The cave contains numerous speleothems as well as large amounts of breakdown and talus associated with the entrance collapse.

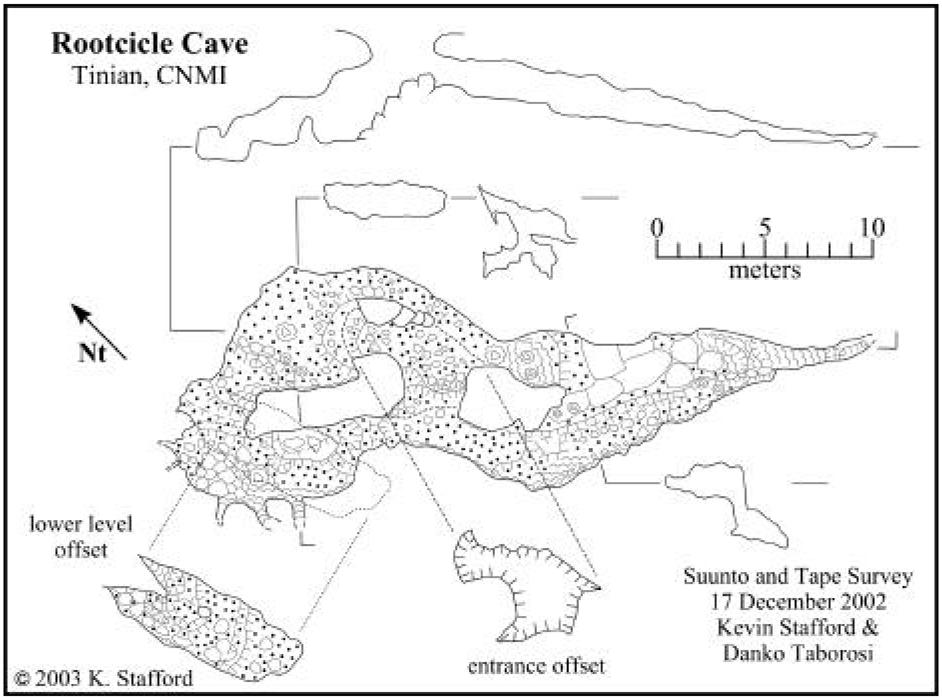

Figure 322: Map of Rootcicle Cave

Flank Margin Caves

Command Post Cave Complex

The Command Post Cave Complex is located approximately150 meters north/northeast of the Lasso Shrine on Mt. *Lasu*. These caves, developed in the Mariana Limestone (QTmca) at the base of the cliff, appear to be breached cliff retreat. These caves were highly modified during WWII for use by the Japanese and include such features as large fortified walls across the entrances and excavated cave floors. Although the caves have been highly modified, the walls and ceiling appear to have little modification. The larger cave is approximately 19 meters by 10 meters, while the ceiling rises to 5 meters in regions. The smaller cave is approximately 4 meters by 9 meters with a ceiling height averaging 1.5 meters.

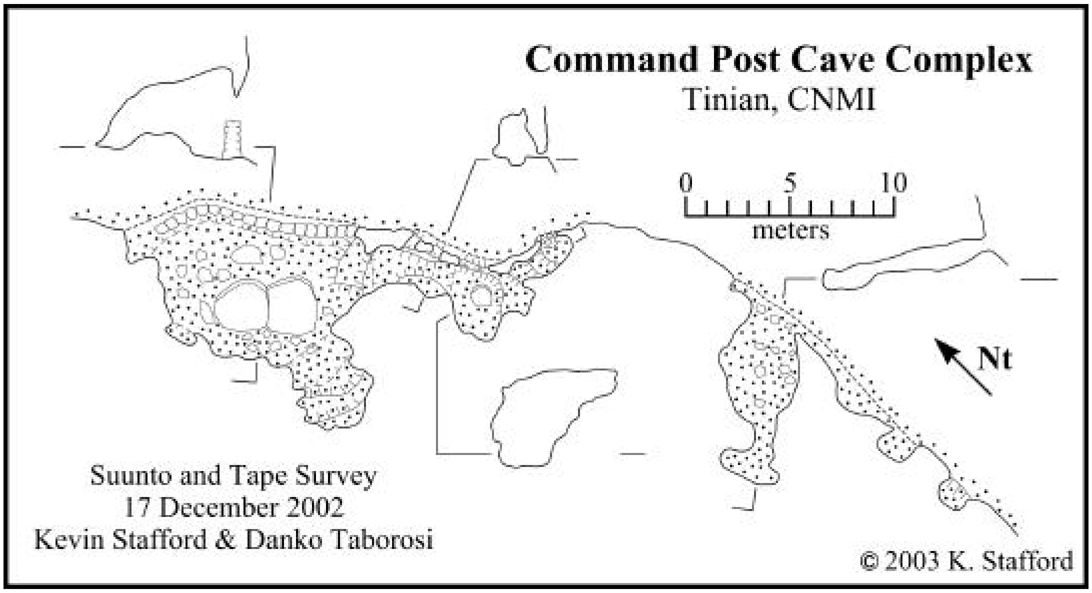

Figure 323: Map of Command Post Cave Complex

Liyang Gntot

Liyang Gntot is located on the northern scarp of Mount *Lasu*, approximately 3600 meters west of *Unai Chiget* in the *Tagpochau* Limestone (Tt). The cave consists of three distinct chambers that extend inland from a common entrance 16 meters wide. The individual chambers average 3 meters tall and 4 meters deep with floors composed of soil, detritus, and scattered breakdown blocks. The feature shows evidence of minor human modification, primarily through leveling of soil floors and was not surveyed at the time of discovery because of time constraints while visiting the region.

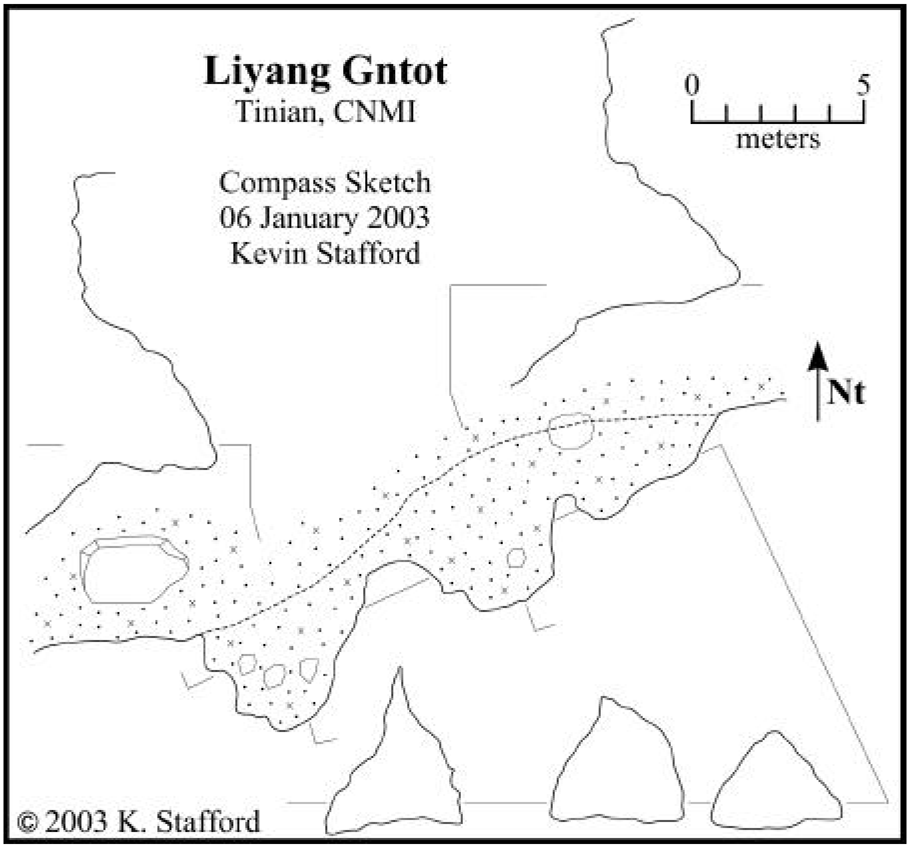

Figure 324: Map of Liyang Gntot

Metal Door Cave

Metal Door Cave is a remnant, flank margin cave located 600 meters east of 8th Avenue on the northern scarp of Mount *Lasu* in the *Tagpochau* Limestone (Tt). It has an entrance area 10 meters wide that is divided by a 2-meter long bedrock column on the south side. The cave extends inland 15 meters with an average ceiling height of 3 meters and several small terrace levels in the inland part. The floor is primarily composed of soil and small rock fragments and has been extensively modified by humans. A 5-meter long, 2-meter tall rock wall conceals the majority of main entrance, while the main portion of the chamber has a leveled floor. The name of the cave is derived from a large metal door that was found 30 meters from the entrance.

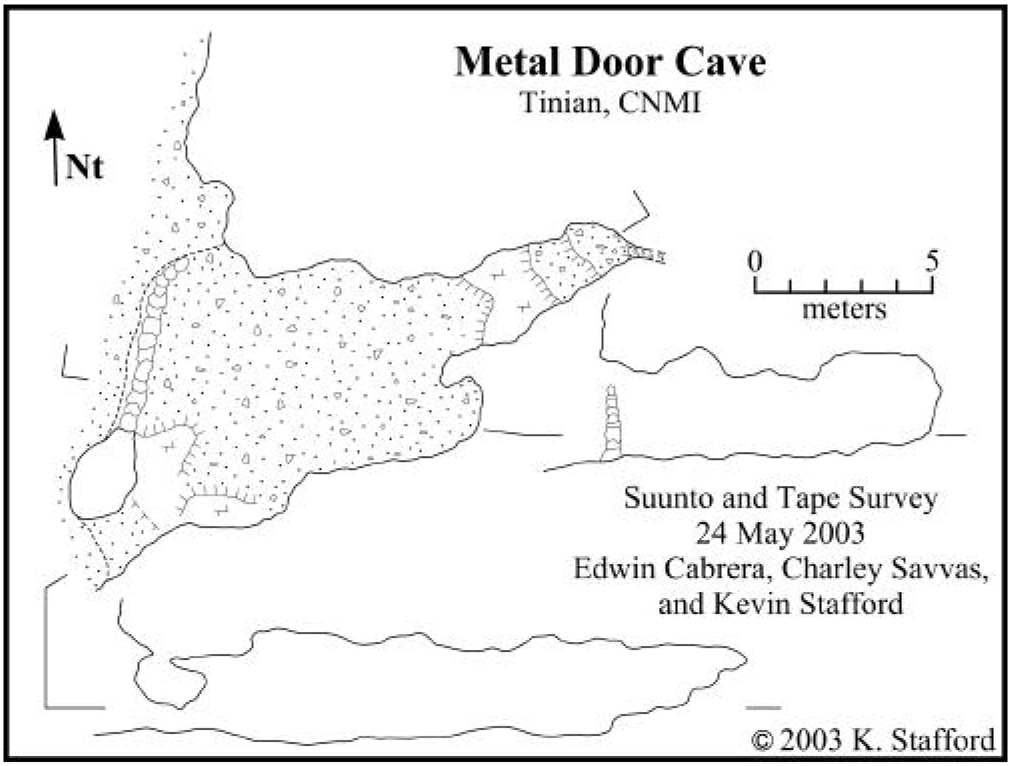

Figure 325: Map of Metal Door Cave

Recharge Cave

Lasu Recharge Cave

Lasu Recharge Cave is located 1100 meters south of Mount *Lasu* on the eastern edge of a large closed depression, where allogenic waters from the igneous outcrops are sinking in the *Tagpochau* Limestone (Tt). This feature, located in a large bamboo grove, has much plant debris at its entrance indicating significant recharge during rain events. The central portion of the feature is a collapsed entrance approximately 2.5 meters deep and oriented along a fracture trending southeast (~135°). The second entrance is located at the western edge of the feature where it meets the large closed depression and is where allogenic water primarily enters the feature. On the western side of the feature, there is another fracture trending southeast (~155°), which forms the far interior wall. Water follows this 20-centimeter, dissolutionally widened fracture to the northwest. Although this feature only measures 6 meters by 9 meters with a total depth of 3 meters, it is significant as a point source recharge feature for groundwater.

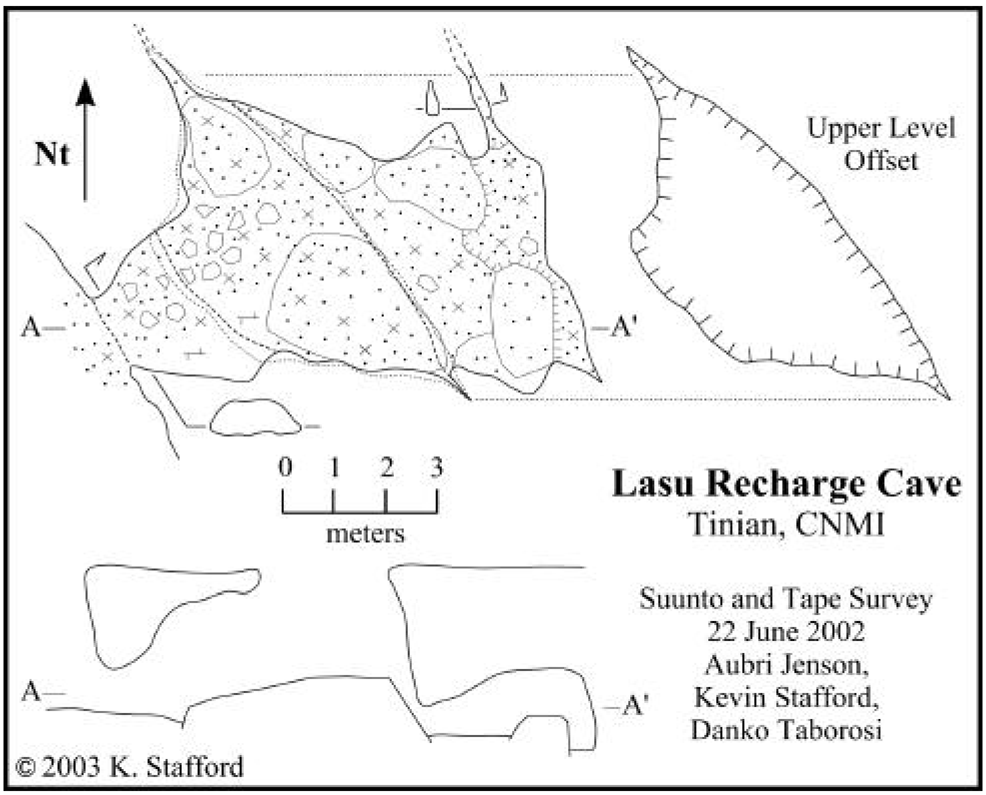

Figure 326: Map of Lasu Recharge Cave

NORTHERN LOWLAND

Discharge Feature

Rogue Cave

Rogue Cave is located 150 meters northeast of *Unai Lamlam* on the northwest coast. It is a discharge type feature developed in the Mariana Limestone (QTmu), extending inland 9 meters from a cove 31 meters wide and 19 meters deep. The majority of the cave is below sea level, but a bench up to 7 meters wide extends from the cave with partially roofed sections. The cave consists of a chamber 3 meters in diameter that extends below sea level 1.5 meters and a smaller tube that extends inland from the chamber 6 meters at 2 meters above sea level. The smaller tube has a distinct fracture or joint, which runs through the ceiling and floor, while a larger, dissolutionally widened fracture extends from the entrance below sea level. The feature showed some indication of freshwater discharge below sea level, but due to strong surf conditions a positive identification of discharge was not possible. However, based on the morphology of the cave and the distinct joint in the floor and ceiling, this feature is classified as a discharge feature.

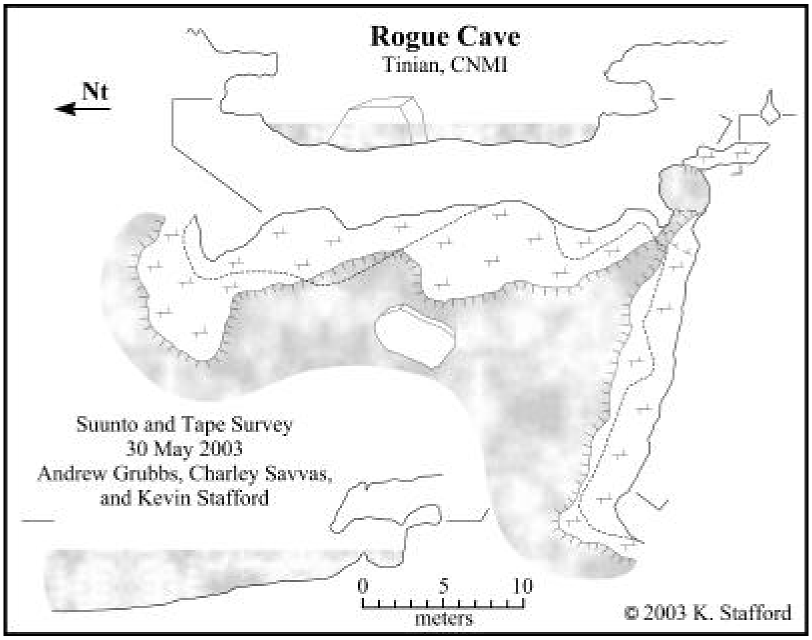

Figure 327: Map of Rogue Cave

Flank Margin Cave

Unai Lamlam

Unai Lamlam is a cove 110-meter wide, extending inland 90 meters in the Mariana Limestone (QTmcc) on the northwest coast. The main part of the cove is along the eastern edge of the feature and extends inland the greatest distance, where it narrows to 18 meters. The western portion of the cove contains two flank margin cave remnants that extend inland 15 meters from their ceiling drip lines, with average heights of 1.5 meters. The more protected interior regions of the cove contain carbonate sand beaches, while the more seaward regions have bedrock floors. In several areas, large breakdown blocks are presents, which appear to be remnants of collapsed ceilings.

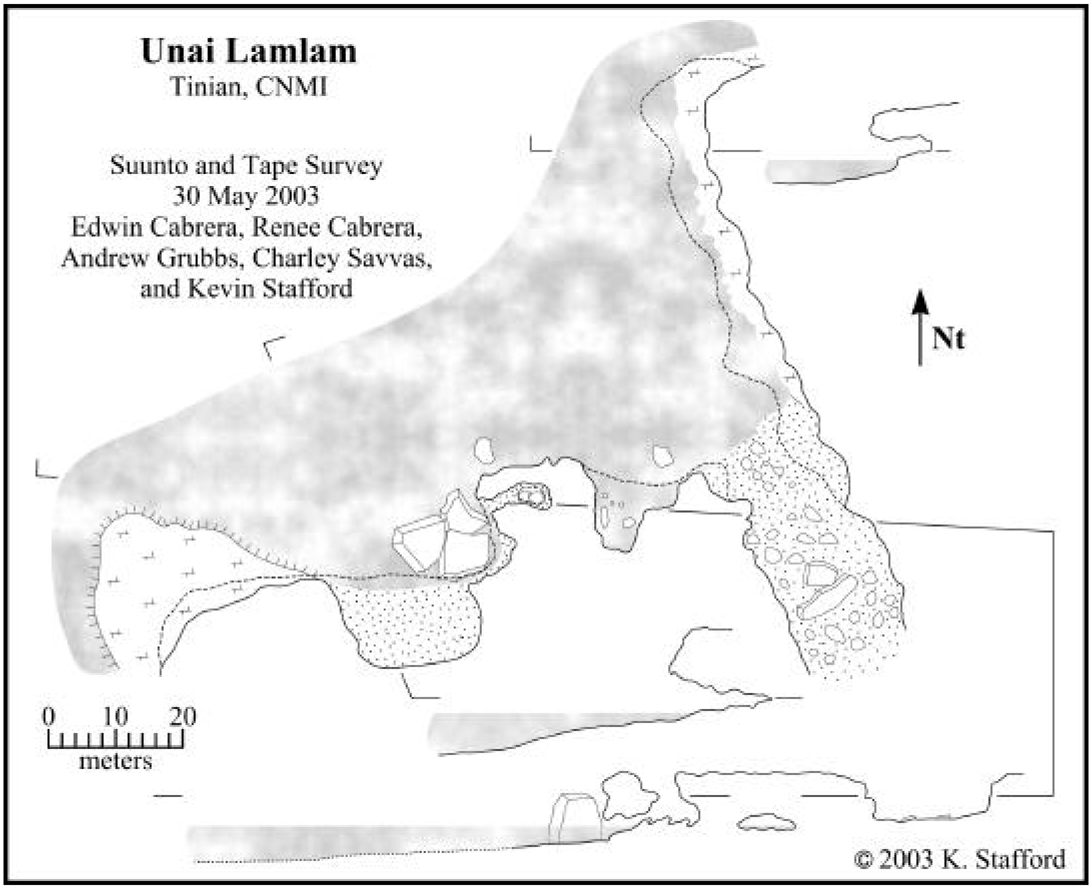

Figure 328: Map of Unai Lamlam

Mixing-Zone Fracture Cave

Unai Chiget

Unai Chiget is located at the boundary between the Central Plateau and the Northern Lowland on the east coast of Tinian where the Northern Lowland has been down-dropped relative to the rest of the island along the *Chiget* fault, which trends 250^{o} in the Mariana Limestone (QTmca). The feature is a small embayment that has an average water depth between 0.5 and 1.5 meters and extends inland for 160 meters along the fault scarp, while cliff retreat and dissolution have widened the region to approximately 30 meters. At the seaward end of the feature, a series of large algal mounds are formed at the coastline, protecting the inland parts of the feature from more extensive wave erosion. The southern wall of the feature extends further inland and has a maximum height of 35 meters near the coastline, while the northern wall averages 4 meters and diminishes in height inland. Along the cliff walls, at sea level and up to 2 meters above sea level, is a well-developed, 1 to 2 meter deep, bioerosional notch. This feature shows extensive dissolution along the fault line and subaqueous grooves indicate that this feature may discharge fresh water, although no definitive evidence was seen.

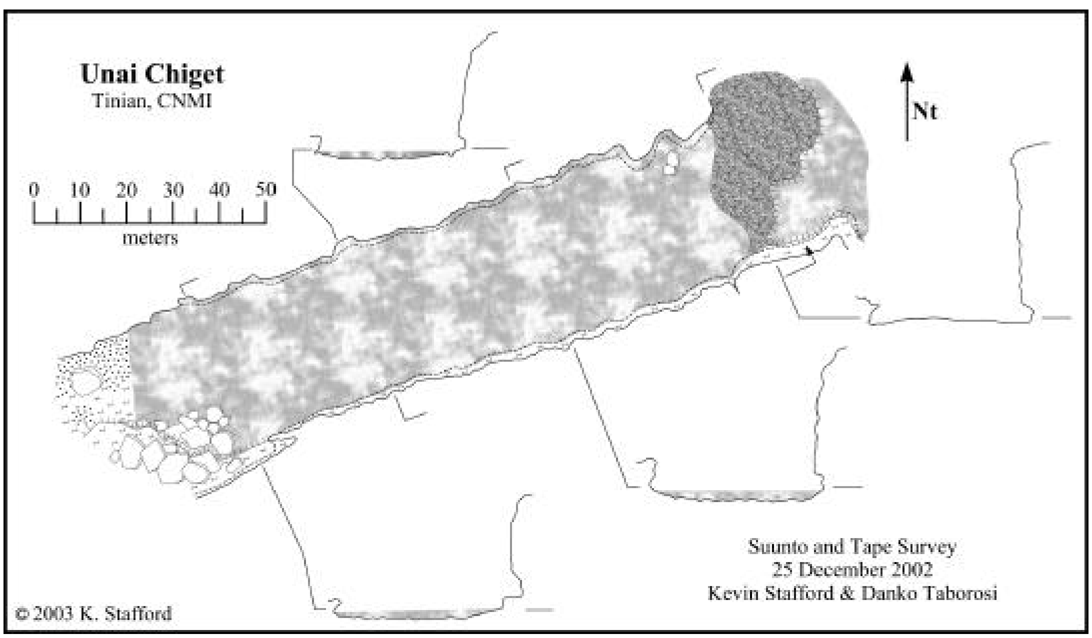

Figure 329: Map of Unai Chiget

SOUTHEASTERN RIDGE

Discharge Feature

Cetacean Cave

Cetacean Cave is located 250 meters southeast of *Unai Masalok* in the Mariana Limestone (QTmu) near and parallel to a large fault scarp, which trends 85^{o}. The cave is developed along a joint that can be observed in the ceiling, while significant freshwater discharges from the fracture in the floor. The cave extends 25 meter inland with and average width of 3 meters and ceiling height between 2 and 3 meters. The entrance area is partially obstructed by two large breakdown blocks, while the presence of numerous fishing net floats wedged into the ceiling joint is evidence of intense wave impact. The majority of the cave has a bedrock floor submerged under 0.25 to 0.5 meters of water with some weathered breakdown blocks and cobbles protruding above water level. It appears that the cave formed by freshwater discharging along a fracture, resulting in the headward dissolution of limestone enhanced by the mixing of fresh and salt waters.

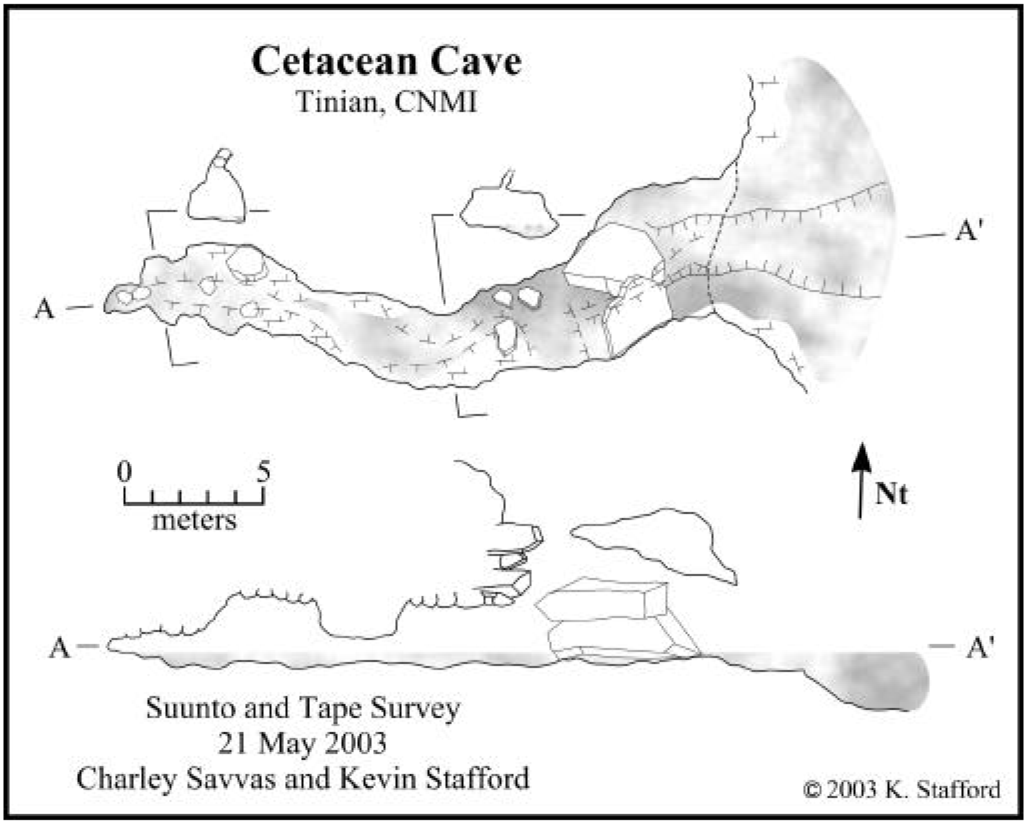

Figure 330: Map of Cetacean Cave

Fissure Caves

Carolinas Fracture Cave

Carolinas Fracture Cave is located in Carolinas Limestone Forest, approximately 500 meters east of the ocean and oriented roughly parallel to the cliff margin. This feature is developed in the Mariana Limestone (QTmu) as a result of the dissolutional widening of a fracture created by cliff margin retreat. The feature trends northeast (~50^{o}) and extends for approximately 70 meters, with an average width of 2 meters and maximum depth of 16 meters. Approximately one half of the feature is roofed with large breakdown blocks, comprising the northeastern portion of the feature, which intersects the cliff line that is retreating. The cave shows extensive speleothems covering the walls in the roofed section with lesser amounts in the unroofed portions.

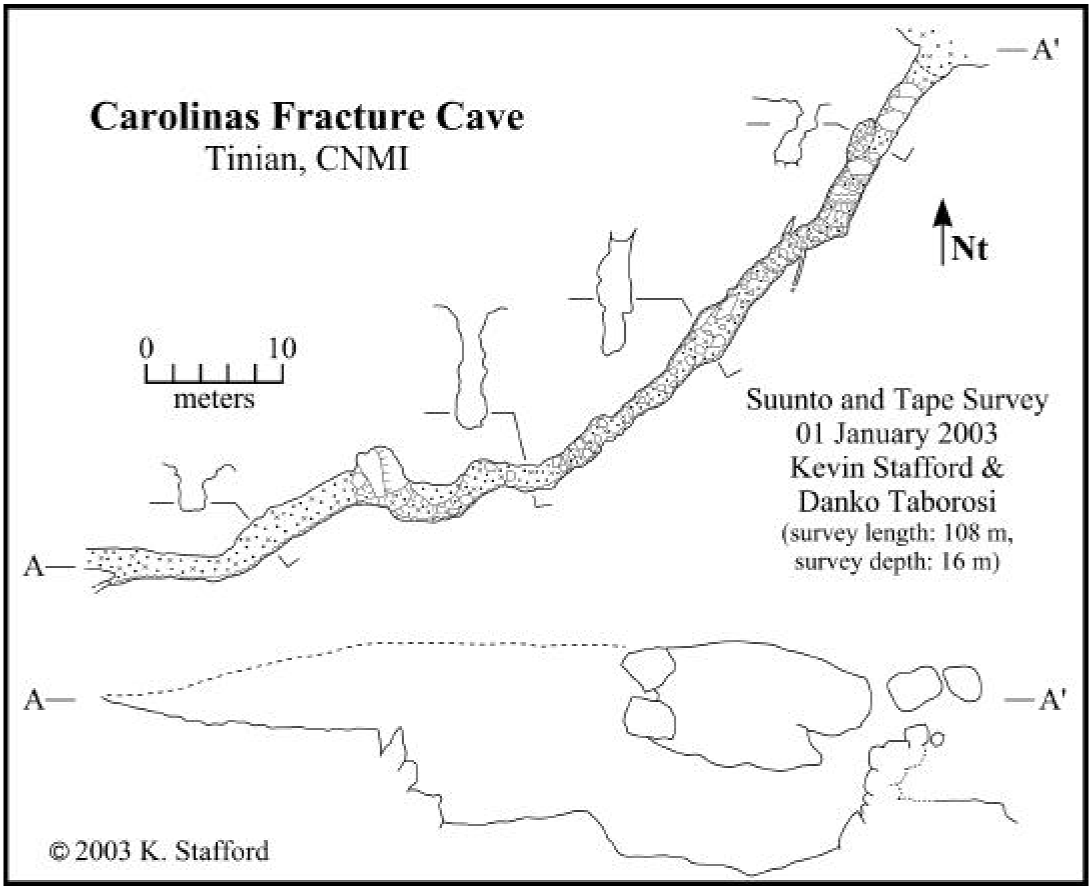

Figure 331: Map of Carolinas Fracture Cave

Danko's Misery

Danko's Misery is located approximately 1000 meters southwest of *Puntan Barangka* along the northeastern cliffs of Carolina's Ridge. It is developed in the Mariana Limestone (QTmca) as a dissolutionally enhanced bank-margin fracture that is oriented northwest at a bearing of 305°. This fracture cave is 24 meters in length, 22 meters deep and has a maximum width of 2 meters. The floor is composed of breakdown, forming three levels that increase in depth to the southwest, which limited exploration. In the general region of Danko's Misery, there are numerous other fractures with the same general orientation, however most of these features are not humanly enterable.

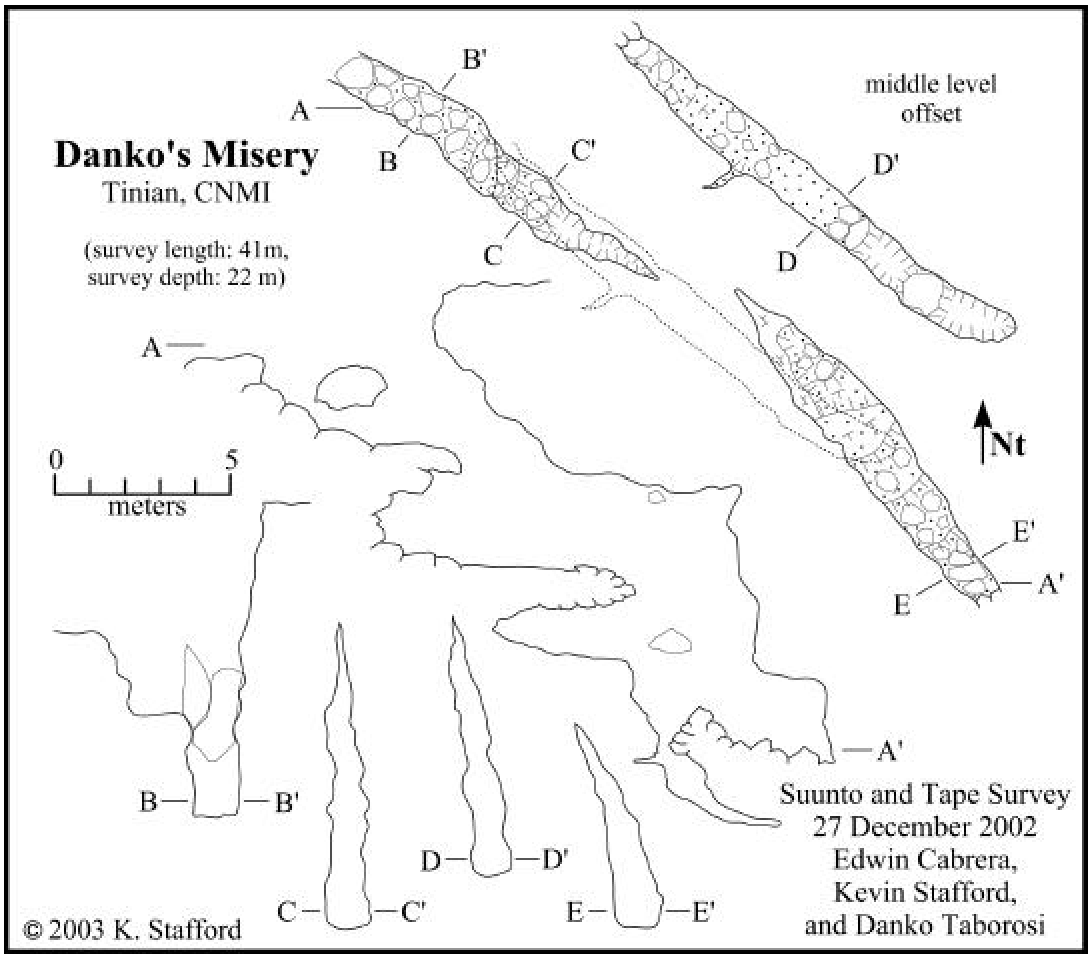

Figure 332: Map of Danko's Misery

Full Bottle Cave

Full Bottle Cave is located approximately 500 meters west/northwest of *Puntan Masalok* in the Mariana Limestone (QTmu). It is developed along a fracture, oriented northwest (~310^{o}) and dipping to the northeast at approximately 60^{o}. The feature is 6 meters deep and up to 6 meters wide. The main chamber extends for 14 meters, but fractures less than 20 centimeters wide extend beyond the main chamber in northwest and southeast directions. The floor is primarily composed of breakdown with indications that the fracture extends to greater depths. Speleothems are primarily concentrated on the southwest wall of the chamber, on the footwall of the fracture. The entrance is located in the southwest portion of the feature amongst numerous breakdown blocks in the northern region of the “600 Meter” Fracture System.

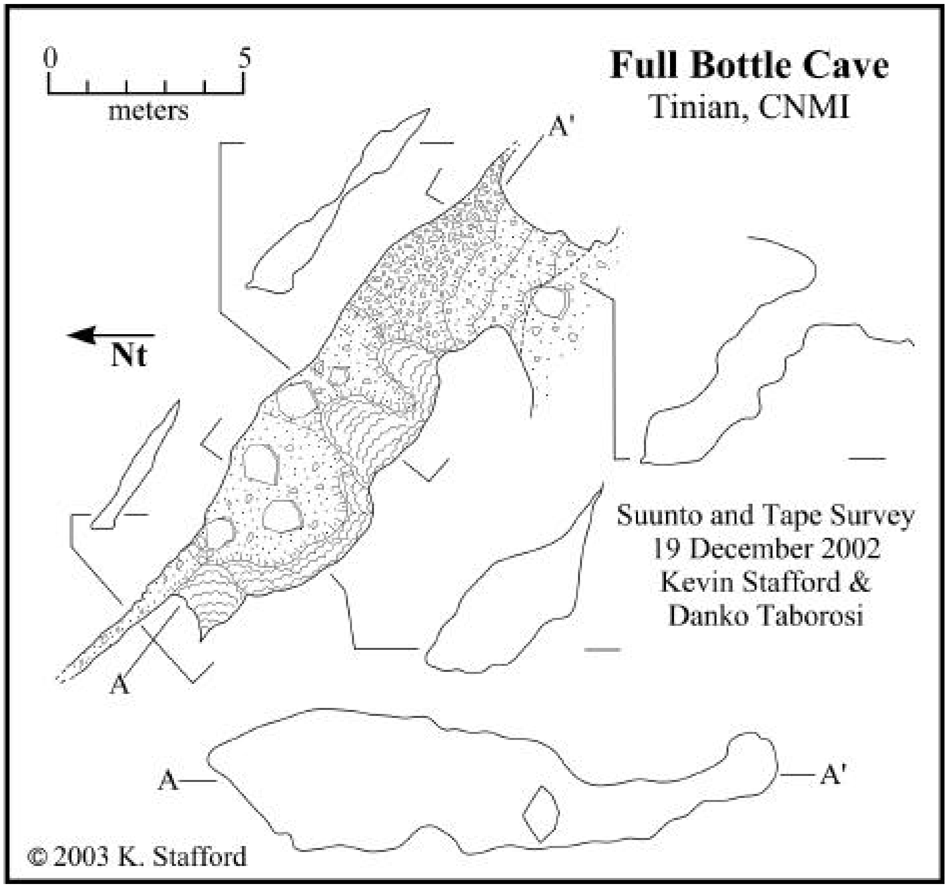

Figure 333: Map of Full Bottle Cave

Liyang Popporput

Liyang Popporput is a fracture cave located approximately 1000 meters southwest of *Puntan Barangka*, along the northeastern cliffs of Carolina's Ridge. It is developed in the Mariana Limestone (QTmca) as a steeply dipping, dissolutionally enhanced fracture that is oriented northwest at a bearing of 80°. This fracture cave is 40 meters long, 23 meters deep and has a maximum width of 2 meters. The feature is located in a region with numerous smaller fractures that cannot be explored as extensively. In the western part of the feature, where there is a partial roof of collapse material, some minor speleothems coat the walls.

Cliff retreat in this region has created a complicated assemblage of fracture caves that are acting as fast flow routes transferring water to the subsurface. It is expected that some of the features in this area extend to greater depths, but are either too small to explore, are blocked by breakdown as in this feature, or have not yet been discovered.

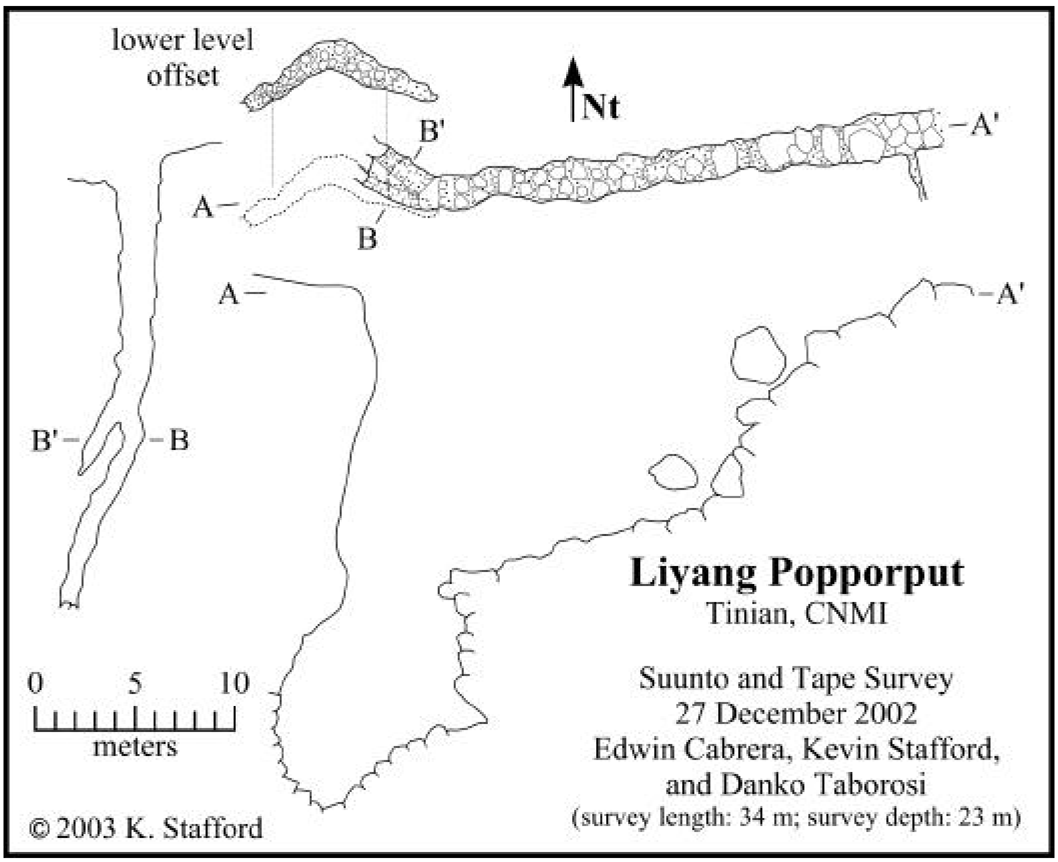

Figure 334: Map of Liyang Popporput

Masalok Fracture Cave Complex

The *Masalok* Fracture Cave Complex is located approximately 300 meters west/northwest of *Puntan Masalok* in the Mariana Limestone (QTmu), along the same fracture as the “600 Meter” Fracture System. This fracture strikes northwest and dips approximately 80^{o} to the northeast. At 42 meters, this feature is the deepest karst feature currently known on the island of Tinian. The main portion of the cave can be reached by a series of climb-downs, but the lower levels require the use of ropes and vertical equipment for safe exploration. Speleothems are common throughout the entire feature, especially in the form of flowstone coating the passage walls. The ceiling is composed primarily of large breakdown blocks, while the floor consists of breakdown and alluvium. Exploration in the main cave, which extends farthest to the northwest, was halted in both the northwest and southeast portions by breakdown. However, exploration in the eastern part of the feature led to the deepest parts of the cave, which includes a 40-meter near-vertical descent from the eastern most entrance. Based on survey data, the main, western part, of the cave and the eastern part of the cave are separated by less than 2 meters of breakdown blocks, confirming that they are effectively one cave. There is ponded fresh-water and a thick layer of mud at the maximum depth, in the eastern part of the cave, indicating that this area of the cave floods during recharge events. This feature demonstrates the importance of fractures as fast flow routes in eogenetic karst.

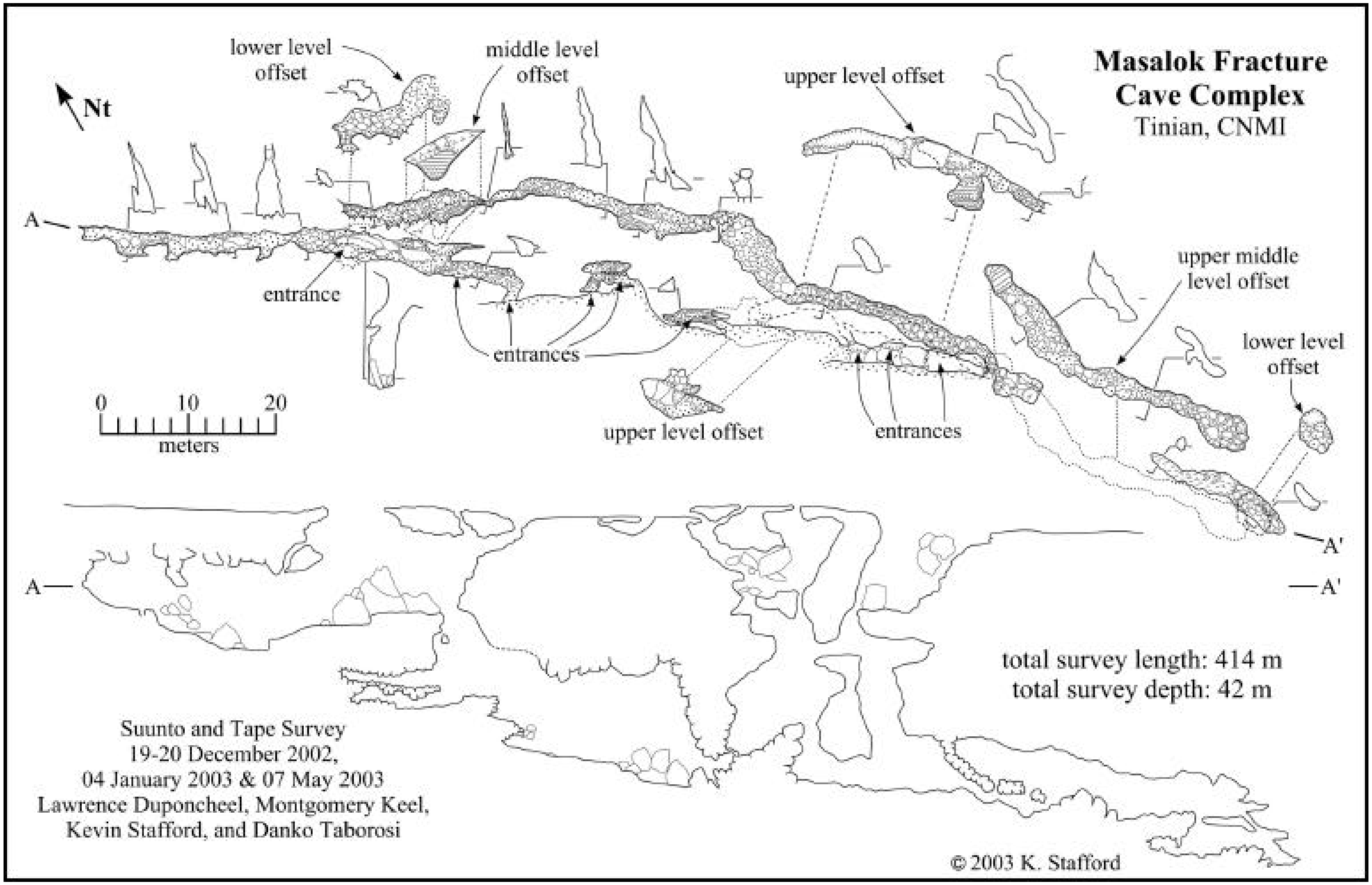

Figure 335: Map of *Masalok* Fracture Cave Complex.

Flank Margin Caves

Bee Hooch Cave

Bee Hooch Cave is located along the southeastern scarp of the Piña ridge in the Mariana Limestone (QTmu). It is a flank margin cave breached by cliff retreat with an entrance width of 12 meters, depth of 9 meters and ceiling height of 4.5 meters. The cave has been extensively modified by humans, including the addition of wooden floors that are highly deteriorated in the northwest and northeast portions of the cave. The cave contains minor amounts of flowstone along the walls and has a floor comprised primarily of soil and small breakdown blocks.

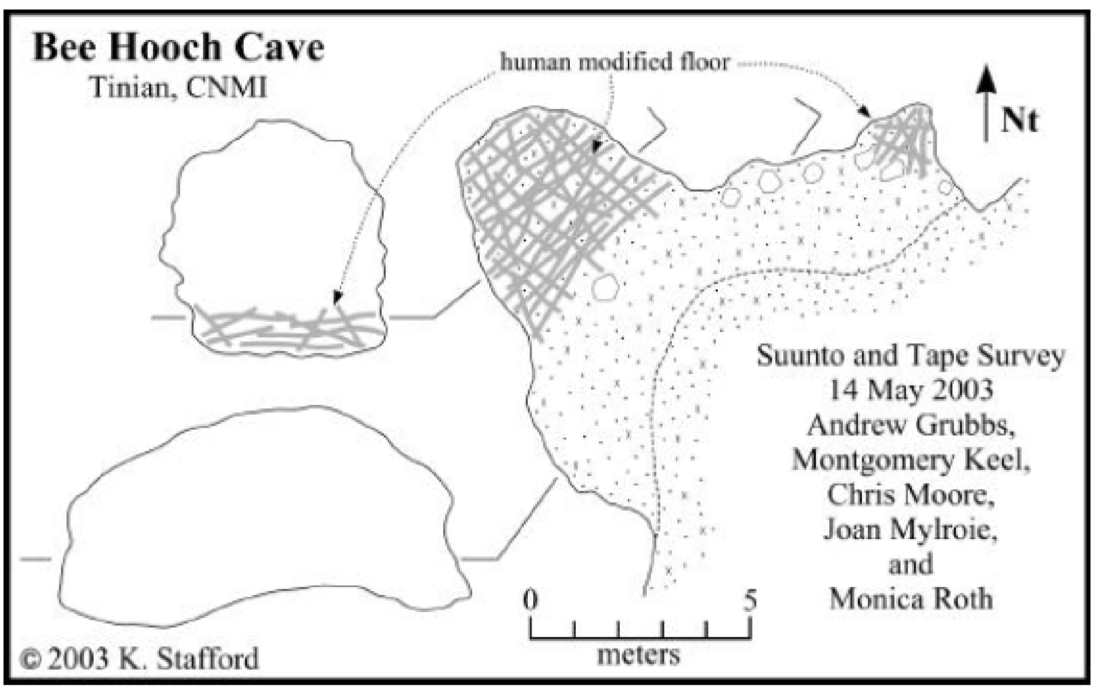

Figure 336: Map of Bee Hooch Cave

Body Repel Cave

Body Repel Cave is a breached, flank margin cave located in the central region of Suicide Cliffs approximately 5 meters below the top of the scarp. It is developed in the Mariana Limestone (QTmu), has a width of 24 meters exposed along the cliff, a depth of 7 meters and maximum ceiling height of 6 meters. This cave remnant represents the inland wall of a larger flank margin chamber that has almost been removed by scarp retreat. The ceiling covers approximately seventy percent of the floor area, which consists of several small terraces.

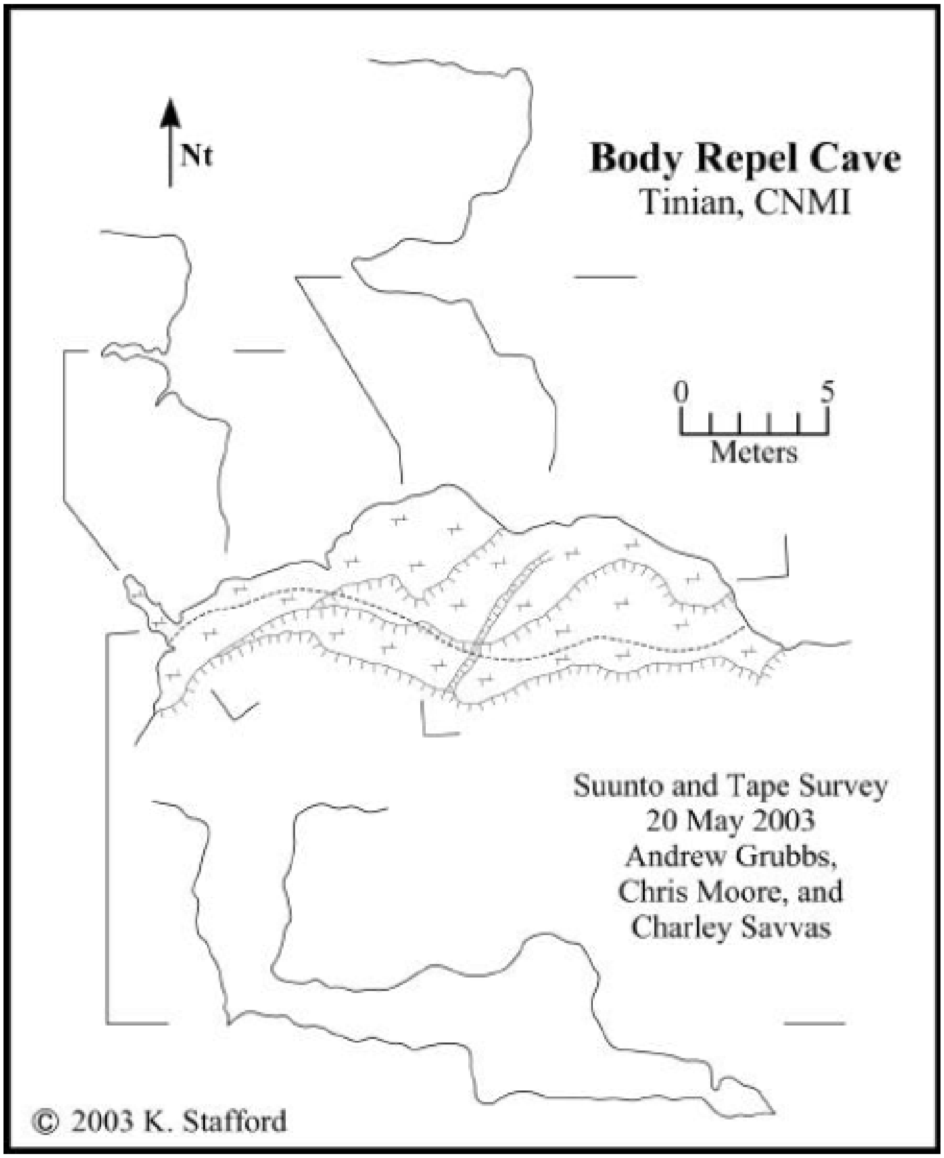

Figure 337: Map of Body Repel Cave

Broken Stal Cave

Broken Stal Cave is located along the southeastern scarp of Piña ridge in the Mariana Limestone (QTmu) and contains limited speleothem deposits except for a single 6-centimeter tall stalagmite in the south-central portion. The main cave remnant is 5 meters wide at the entrance and splits into two smaller passages that join 6 meters inland. The cave is 4 meters tall in the entrance area where the floor is composed of soil and detritus, but the floor is elevated at a 2-meter tall ledge, 1-meter inland from the cave entrance, where the floor becomes bedrock. A 1-meter wide, 2-meter deep bedrock column separates the two passages, while an additional 1 to 2 meters of bedrock separate the main cave from a smaller cave remnant to the south.

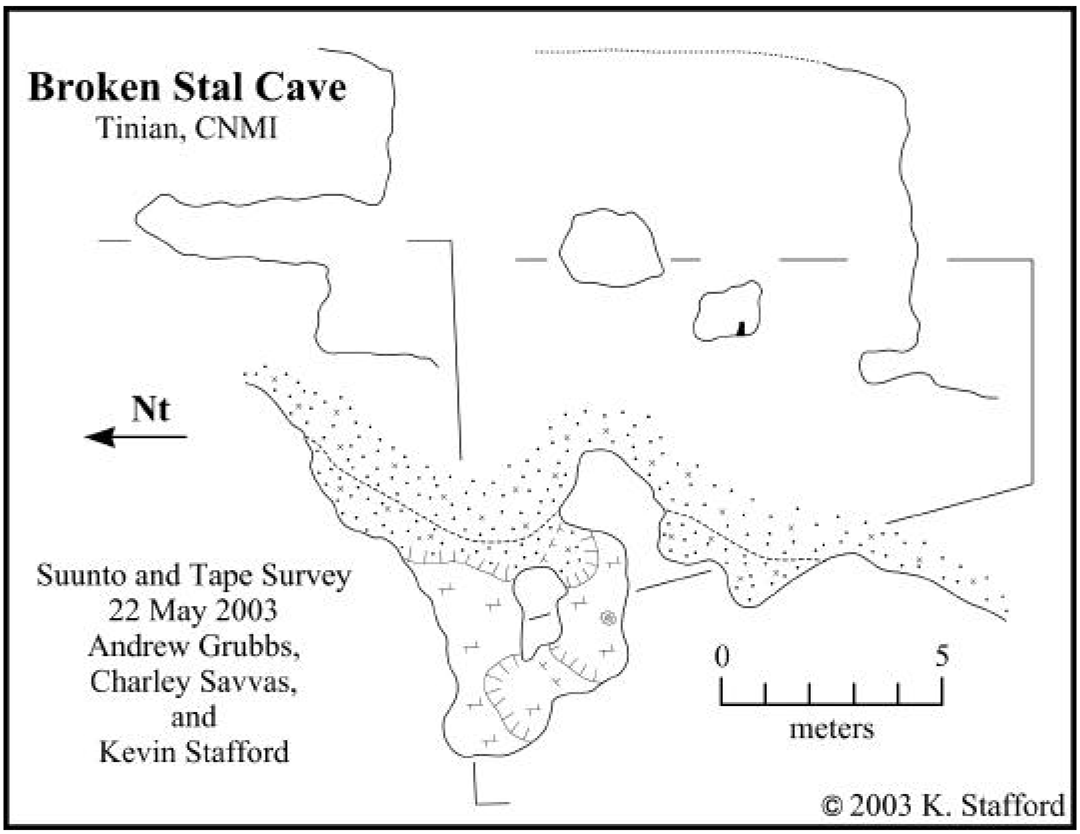

Figure 338: Map of Broken Stal Cave

Cave Without a Cave

Cave Without a Cave is an extreme end member of a remnant flank margin cave breached by cliff retreat. It is located in the central portion of Suicide Cliffs, approximately 20 meters above the base of the cliff and is developed in the *Tagpochau* Limestone (Tt). This feature is 20 meters wide, 5 meters deep, 5 meters tall and apparently represents the most inland wall of a flank margin cave. The cave has undergone extensive erosion, but some minor speleothems are present.

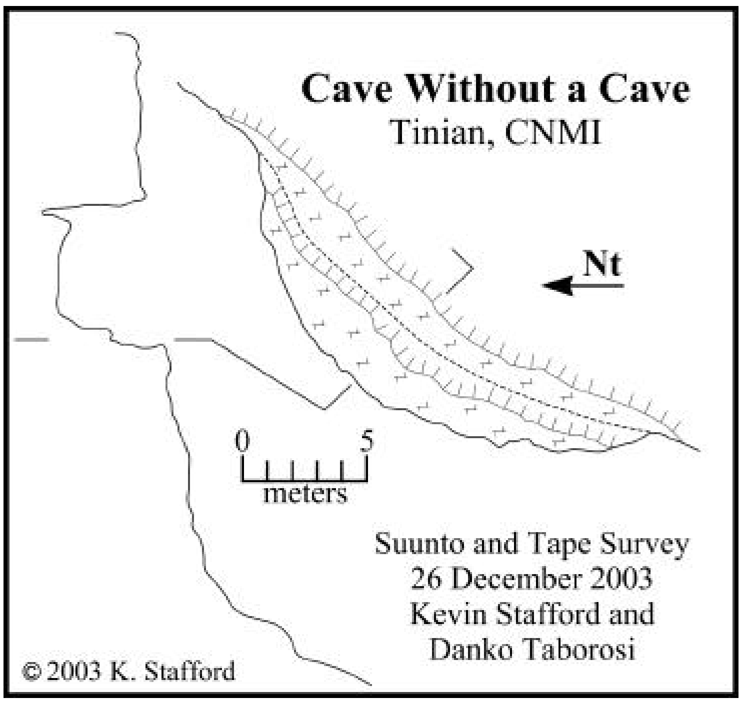

Figure 339: Map of Cave Without a Cave

Cave Without a Roof

Cave without a Roof is an intersected flank margin cave located in the central portion of Suicide Cliffs, approximately 25 meters above the base of the cliff, developed in the *Tagpochau* Limestone (Tt). It is a single, remnant chamber that is 5 meters by 14 meters in size, with a ceiling height of 5 meters. The cave contains only minor speleothems possibly because it has undergone extensive collapse as part of cliff retreat. The roof is missing in most portions of the cave, representing an intermediate stage in the process of cliff retreat where the cave has not only been breached, but the cave roof has been removed by erosional processes.

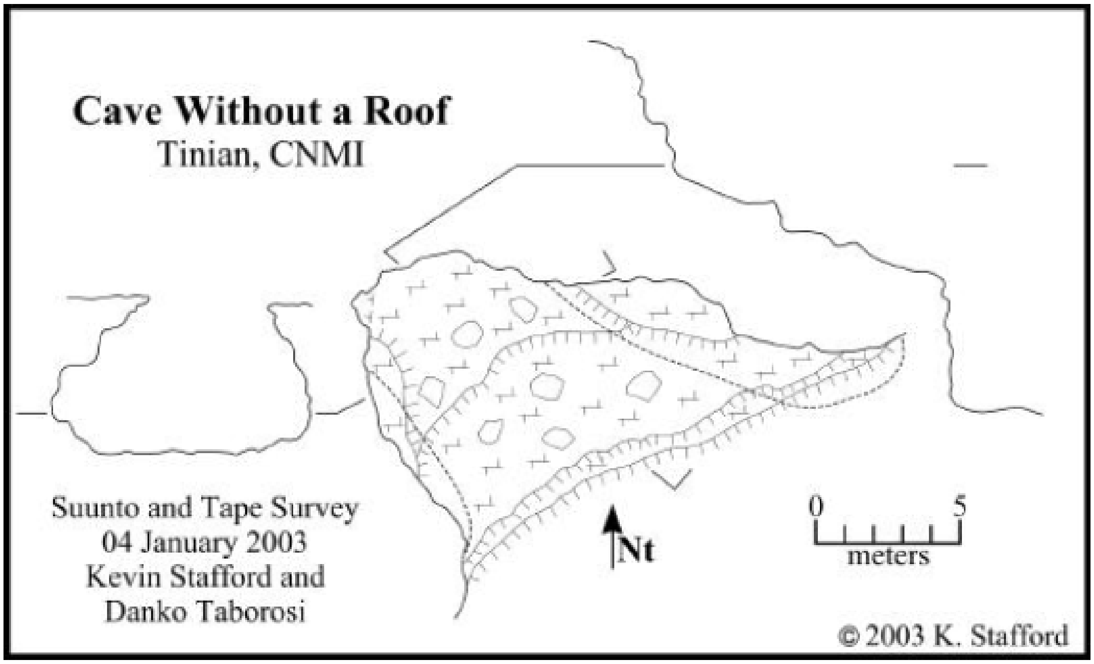

Figure 340: Map of Cave Without a Roof

Coconut Trap Cave

Coconut Trap Cave is located in the southeastern region of the Piña ridge and developed in the Mariana Limestone (QTmu). This small, flank margin cave remnant has an entrance 5 meters wide and extends inland 5 meters with an average ceiling height of 2 meters. The cave has a small flowstone mound that partially separates the entrance area from the inland portions and has a floor composed of soil and detritus.

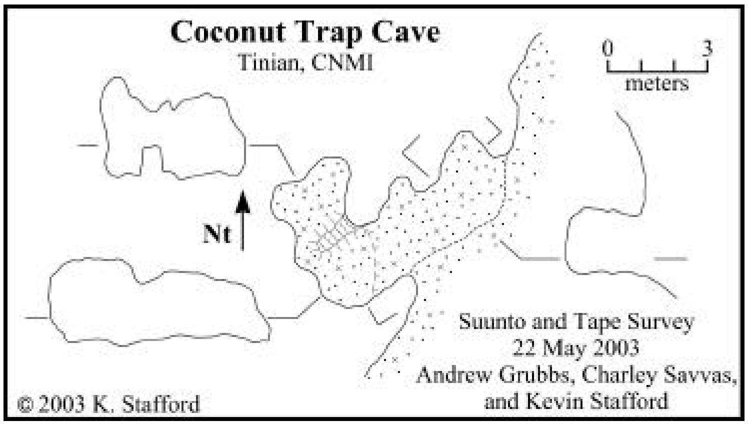

Figure 341: Map of Coconut Trap Cave

East Suicide Cliff Cave

East Suicide Cliff Cave, a breach flank margin cave at the far eastern portion of Suicide Cliffs, was originally named Suicide Cliff Cave #1 (Stafford et al., 2002). This feature, developed in the Mariana Limestone (QTmu), contains several entrances, including a ceiling entrance. The feature is 20 meters wide and extends inland for 6 meters with a maximum ceiling height of 7 meters. The feature has some speleothems and has been modified by humans, including the construction of a partial rock wall across the two largest entrances in the eastern portions of the cave. The main chamber descends approximately 2 meters through a small passage to the north, where it connects to a second smaller chamber breached along the cliff.

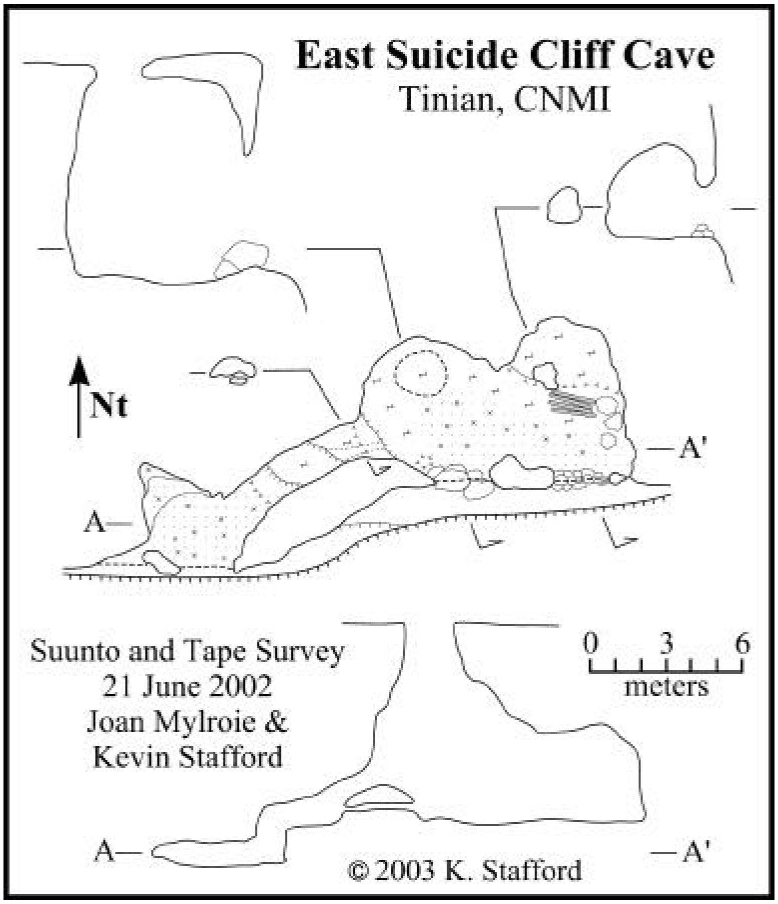

Figure 342: Map of East Suicide Cliff Cave

Elevator Cave

Elevator Cave is located in the central region of Suicide Cliffs in the Mariana Limestone (QTmu). This flank margin cave, composed of two distinct levels, has been breached by cliff retreat on the southeastern side and by roof collapse on the northwestern side. The upper level contains the two mentioned entrances with a cliffside width of 9 meters which narrows to 2 meters wide 3 meters inland where it continues for an additional 7 meters through a passage 1.5 meters tall. The lower level is 7 meters below the upper level and exhibits a similar entrance width, but extends inland only 3 meters. The two levels are connected by a series of small ledges, while the floor throughout is primarily bedrock with alluvium in the area near the collapsed roof entrance. The cave was named for its vertical extent, which is greater than most caves observed at Suicide Cliffs.

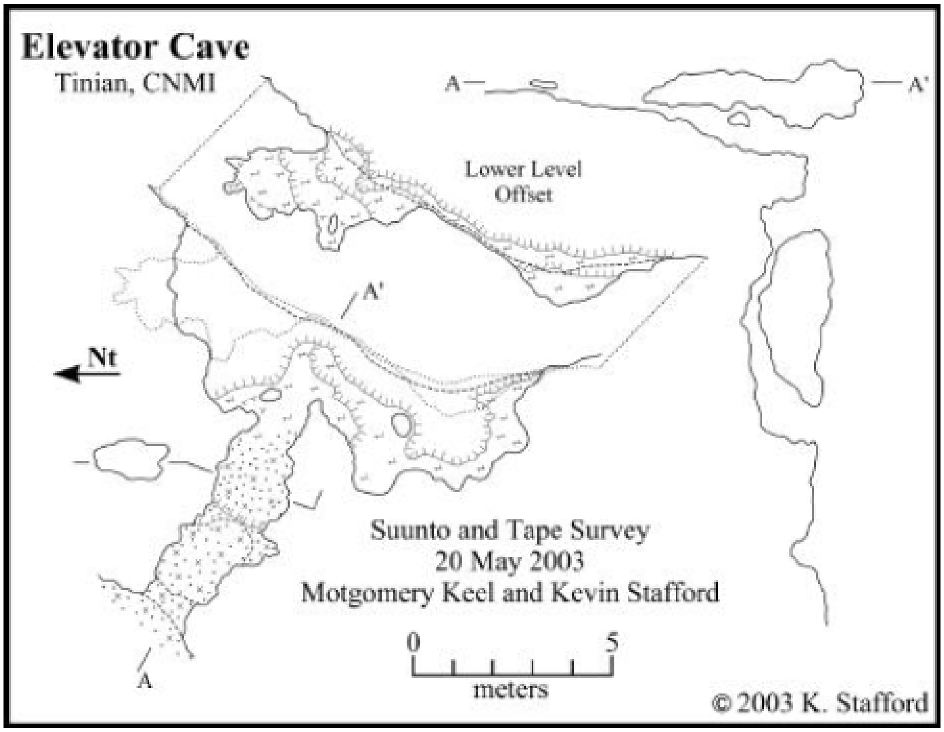

Figure 343: Map of Elevator Cave

False Floor Cave

False Floor Cave is located in the southeastern region of the Piña ridge in the Mariana Limestone (QTmu). The cave is widest at the entrance (17 meters) and extends inland as two chambers. The south chamber extends inland 4 meters with a chamber 6 meters wide and a partial rock wall in the entrance area. The northern, larger chamber extends inland 9 meters and has been significantly modified by humans, including a large rock walled terrace that is 3 meters inland and 2 meters wide and a 1-meter deep excavated area covered by a deteriorating wooden floor. The majority of the cave is floored with soil and detritus with bedrock floors in the most interior regions of the northern chamber.

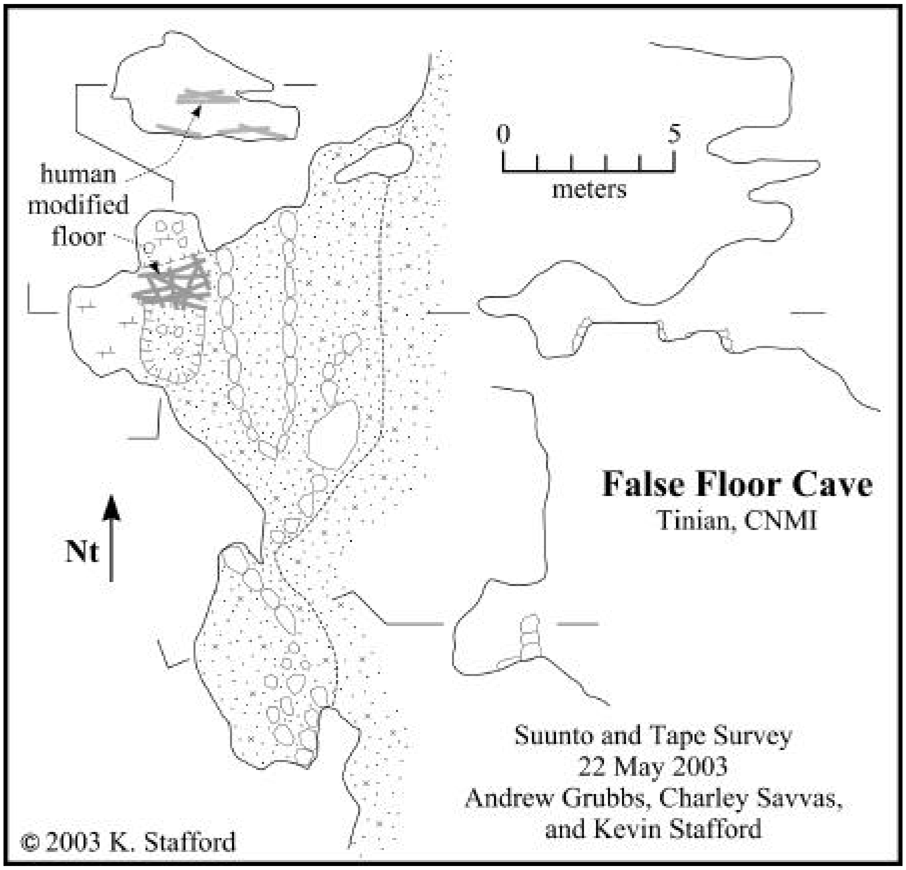

Figure 344: Map of False Floor Cave

Five Bee Cave Complex

Five Bee Cave Complex is located 1900 meters southwest of *Puntan Barangka* on the north side of the Carolinas ridge in the Mariana Limestone (QTmc). This cave complex is consists of two flank margin remnants and a prominent notch in the scarp that is 12 meters wide and 10 meters deep. The notch contains two dissolutionally widened fractures in the northeast and southeast corners that define the notch boundaries. The cave remnant north of the notch extends inland 6 meters as two small partial chambers, while the southern remnant extends inland only 2 meters but has flowstone deposits on the inner wall. The entire complex is 40 meters long and has a soil floor throughout.

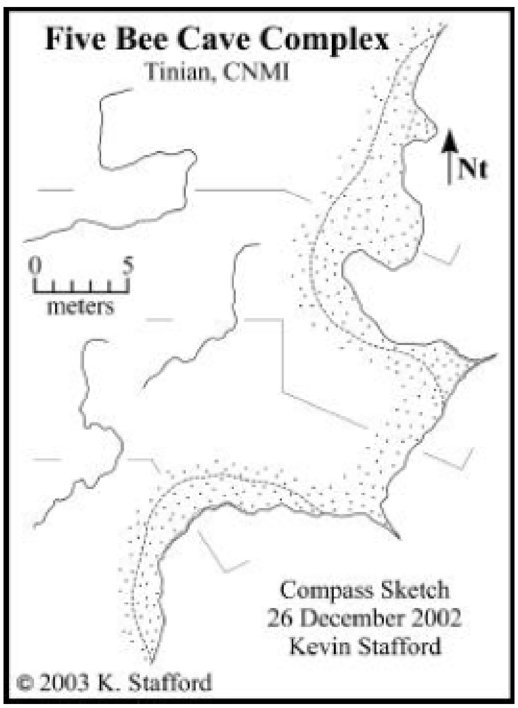

Figure 345: Map of Five Bee Cave Complex

Hermit Crab Cave

Hermit Crab Cave is located in the southeast region of the Piña ridge in the Mariana Limestone (QTmu). It is a small, flank margin cave remnant developed 6 meters above the base of the scarp extending inland 6 meters with an average height of

3 meters. The floor is composed of detritus and soil with a prominent mound located in the middle of the 2.5 meter wide passage. The cave, which contained several hermit crabs at the time of survey, is easily reached by a short climb.

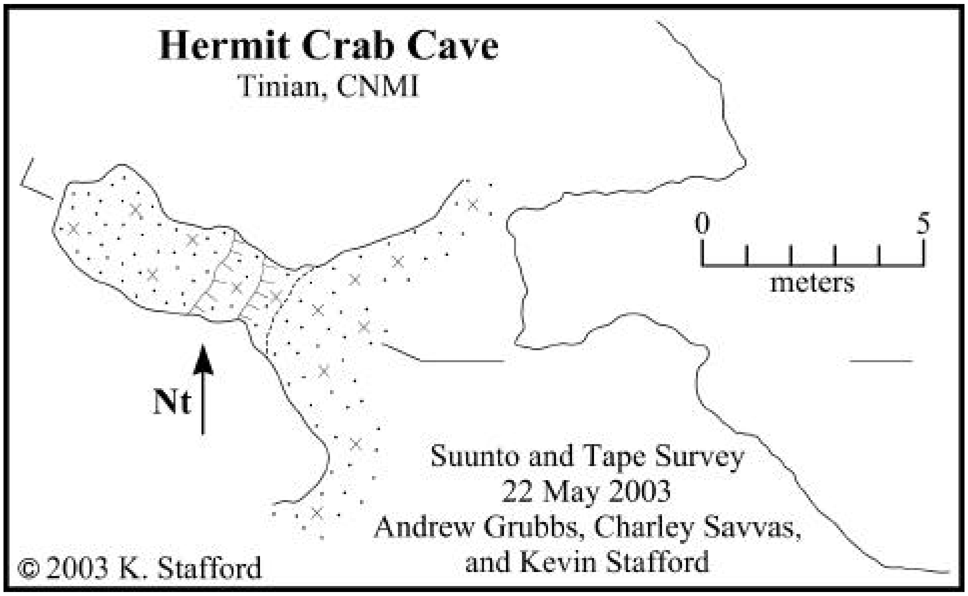

Figure 346: Map of Hermit Cave

Liyang Barangka

Liyang Barangka is a large, collapsed, flank margin cave located on the east coast, 600 meters north/northwest of *Puntan Barangka* in the Mariana Limestone (QTmu). The feature is 65 meters long, up to 50 meters wide and 15 meters deep. The majority of the feature does not retain a roof, but large breakdown blocks covering the bedrock floor throughout the feature appear to have once formed the roof. Ceiling remnants occur along the edges of the feature, extending less than 5 meters from the walls, while a single, small, covered chamber extends from the southwest corner of the feature for 6 meters. The eastern region of the feature extends below sea level and the entire feature shows evidence of impacts from intense storm events. The walls have flowstone deposits, while numerous large breakdown blocks in the central area have eroded speleothems on them. This feature is similar to the coves near *Unai Dangkolo*, but appears to be more severely impacted by coastal processes.

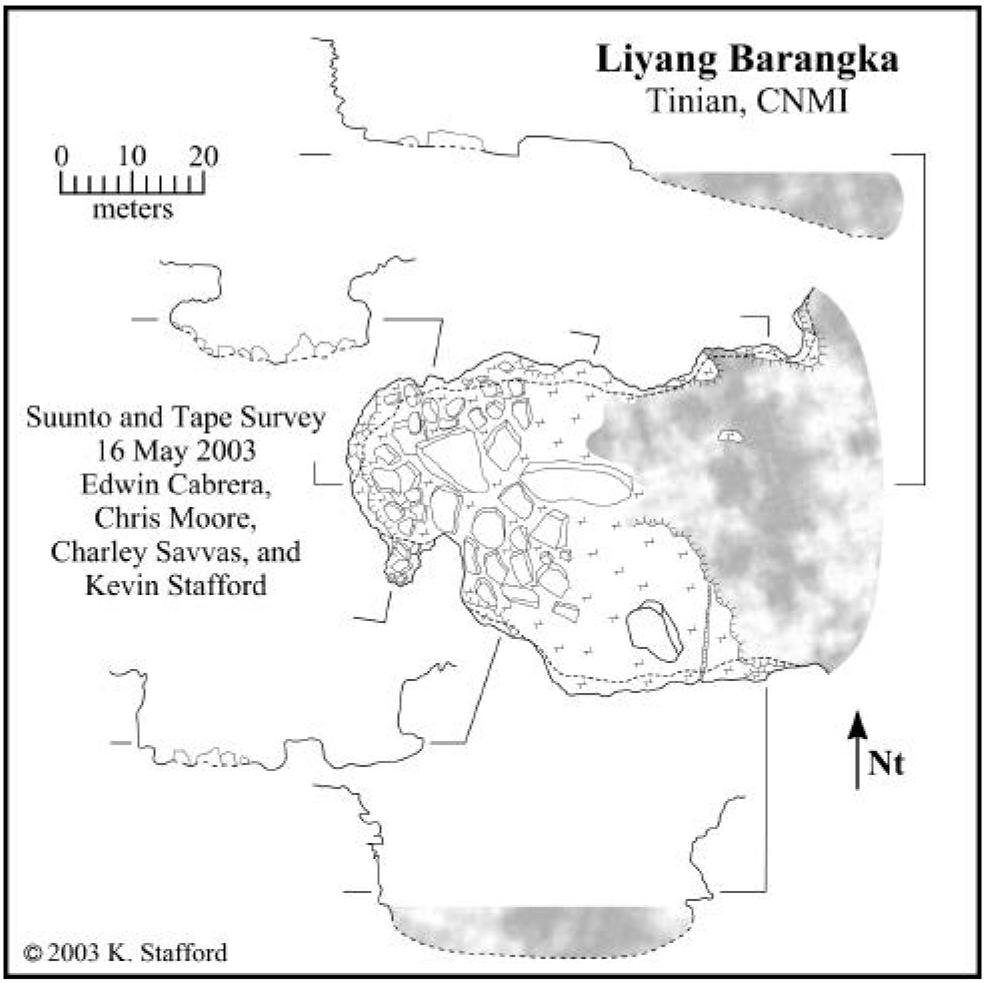

Figure 347: Map of Liyang Barangka

Liyang Mohlang

Liyang Mohlang is located in the north central part of Carolina's Ridge, in the *Tagpochau* Limestone (Tt). Two entrances are present in the northwestern portions of the cave, with the larger one containing a concrete staircase. The feature is 20 meters deep, 25 meters wide and 34 meters long, consisting of a chamber with by a large bedrock pillar. Speleothems are extensive in the eastern part of the cave, while the part is dominated by breakdown. The overall morphology of the cave appears to be that of flank margin cave; however, the large accumulation of breakdown, with a ceiling that shows little evidence of collapse, complicates this interpretation.

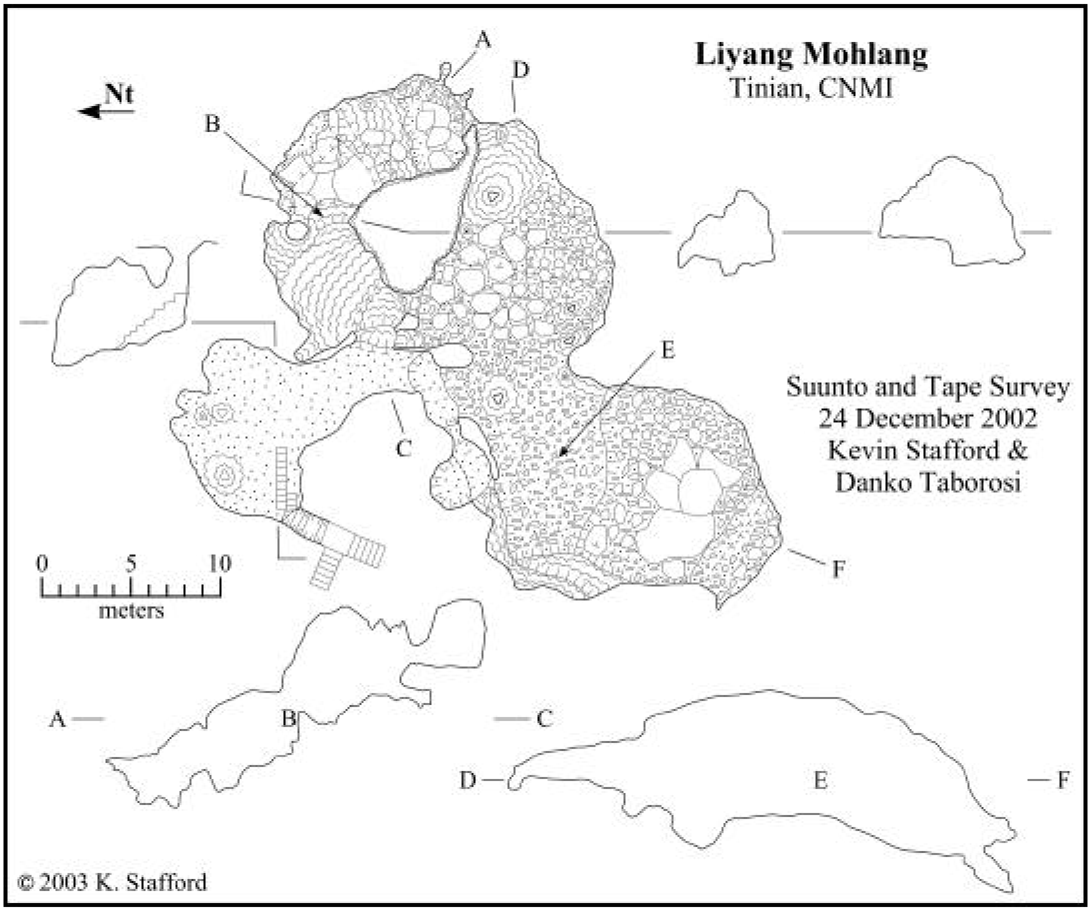

Figure 348: Map of Liyang Mohlang

Lower Suicide Cliff Cave Complex

Lower Suicide Cliff Cave Complex is located near sea level, 2100 meters southwest of *Puntan* Kastiyu in the Mariana Formation (QTmu). It consists of a series of breached flank margin caves along a 190-meter. The cave complex is separated from the ocean by a series of algal-rimmed pools and extends inland up to 50 meters from the coast. The northern cave extends inland 25 meters with an average width of 10 meters. South of the northern cave is a long natural arch that retains an outer wall that is less than 3 meters, forming a 7-meter wide, 10-meter tall, and 50-meter long passage. South of the natural arch passage, three remnant cave chambers extend inland with development that trends inland and up the seaward dipping beds. The southern end of this cave complex is bounded by several large breakdown blocks produced from regional cliff retreat. This complex of caves provides and excellent example of lithologic control on the development of flank margin caves.

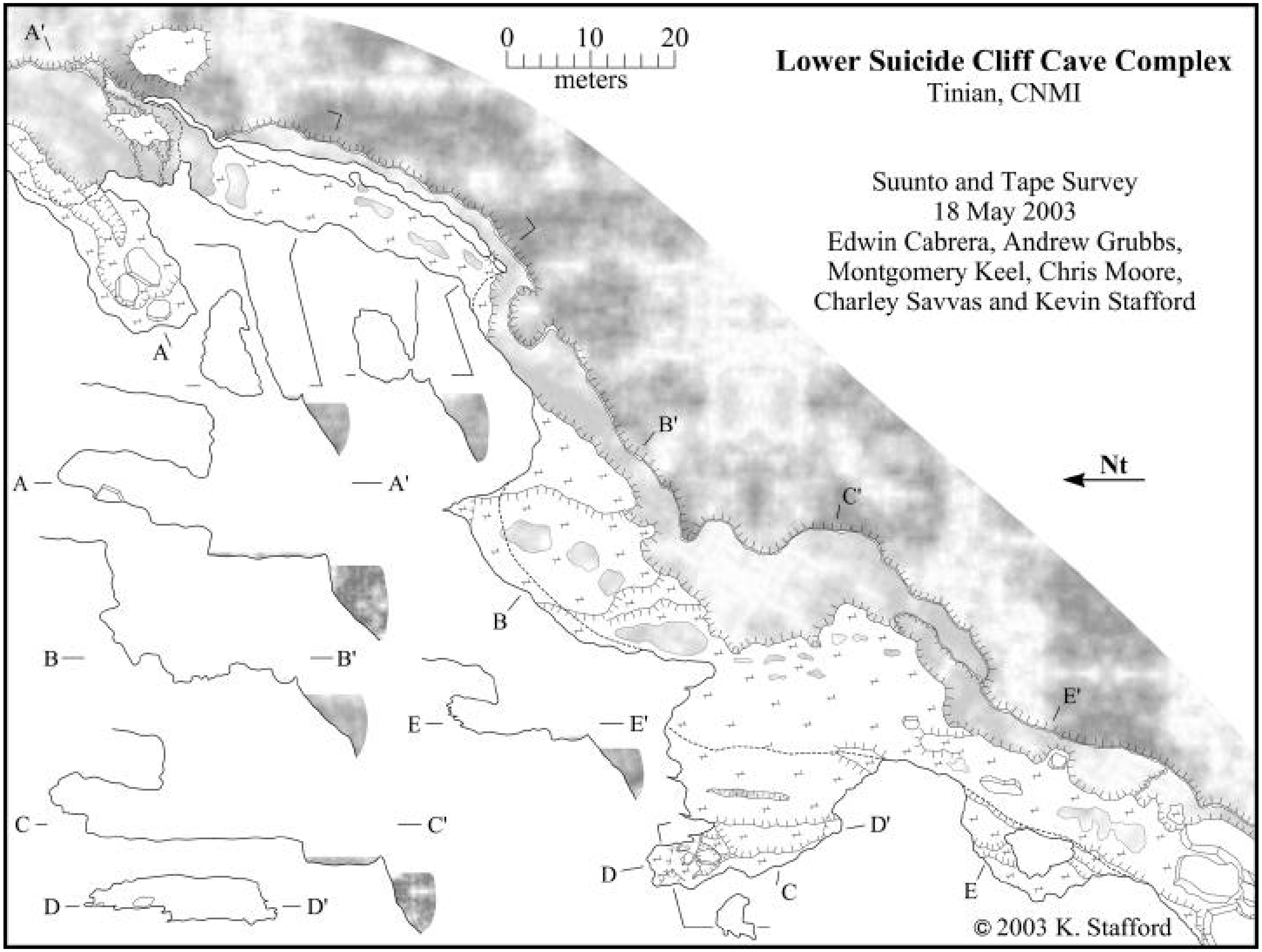

Figure 349: Map of Lower Suicide Cliff Cave Complex.

Metal Stretcher Cave

Metal Stretcher Cave is located in the central portion of Suicide Cliffs, 25 meters above the base of the cliff. This feature is developed in the *Tagpochau* Limestone (Tt) and represents a remnant flank margin cave exposed by cliff retreat. It measures 12 meters wide at the entrance and extends inland 8 meters with a ceiling height of 6 meters. The feature contains speleothems, including two large columns in the entrance area. The cave appears to have had minor human modification in the entrance floor area, but is primarily in its original condition with only minor alluvium covering the floor.

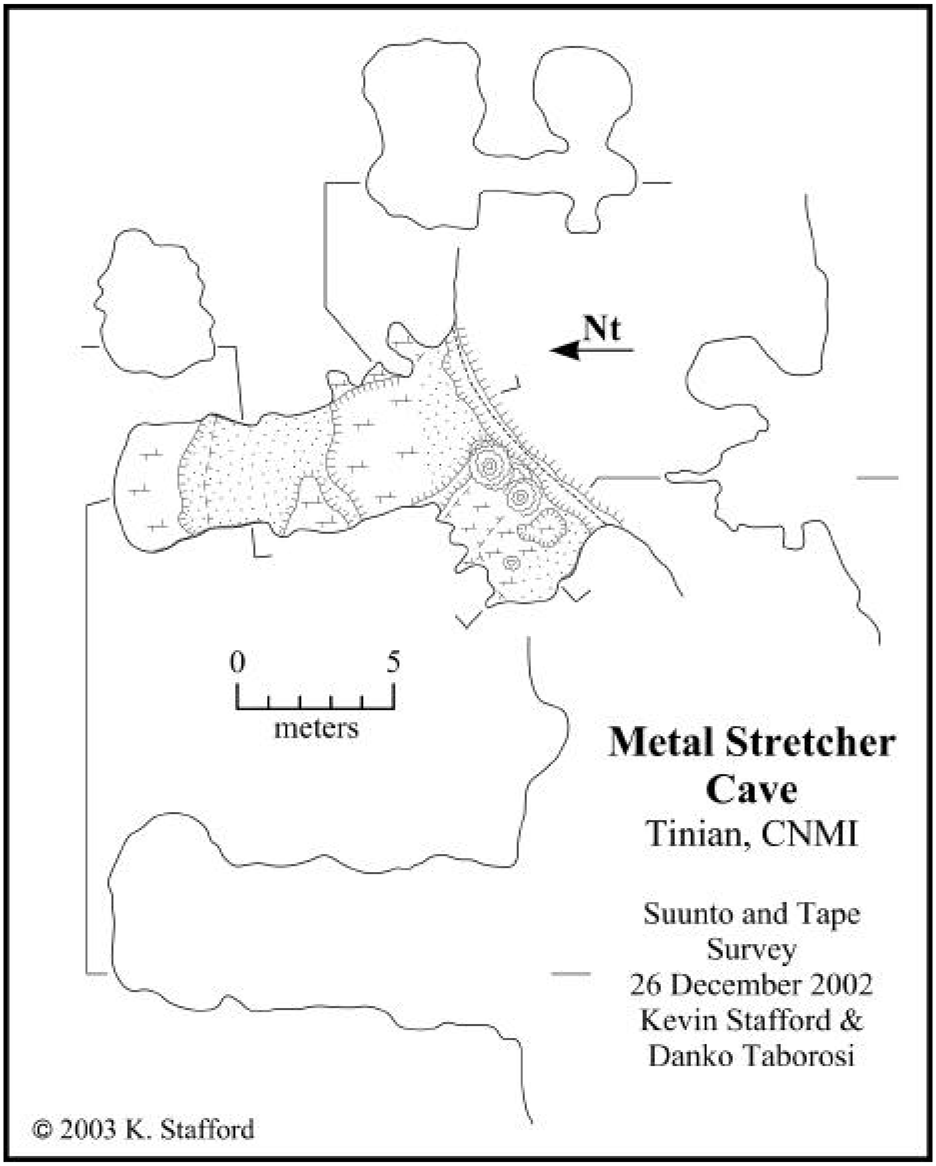

Figure 350: Map of Metal Stretcher Cave

Modified Cave

Modified Cave is located in the central portion of Suicide Cliffs, at the base of the cliff, in the *Tagpochau* Limestone (Tt). The feature is a flank margin cave, which has extensive human modification to the entrance chamber, but little modification other than floor morphology in the larger, northern chamber. The feature is 9 meters by 4 meters with a maximum ceiling height of 3 meters. The larger chamber is a typical small, flank margin chamber with some ceiling collapse. This feature, although modified in the entrance area, represents a second horizon of dissolutional development along Suicide Cliffs, with the other prominent horizon located approximately 20 meters higher.

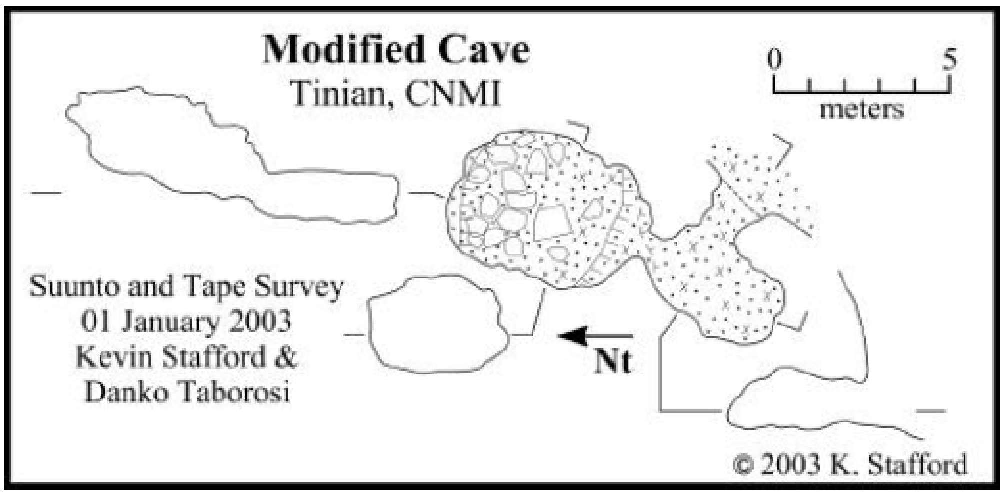

Figure 351: Map of Modified Cave

Northern Playground Cave

Northern Playground Cave is located in the southeast region of the Piña ridge and consists of two caves developed in the Mariana Limestone (QTmu). The larger cave has an entrance 5 meters wide that is 6 meters tall and extends inland 6 meters with a 2-meter wide and 2.5 meters tall passage extending from the southwest corner of the main chamber for 4 meters. The smaller cave is located 4 meters northeast of the larger cave and extends inland 4.5 meters with an average width of 3 meters and ceiling height of 2 meters. The majority of the cave is floored with soil and detritus, but a small ledge in northern portion of the larger cave is bedrock as is the passage extending from the southwest corner of the larger cave.

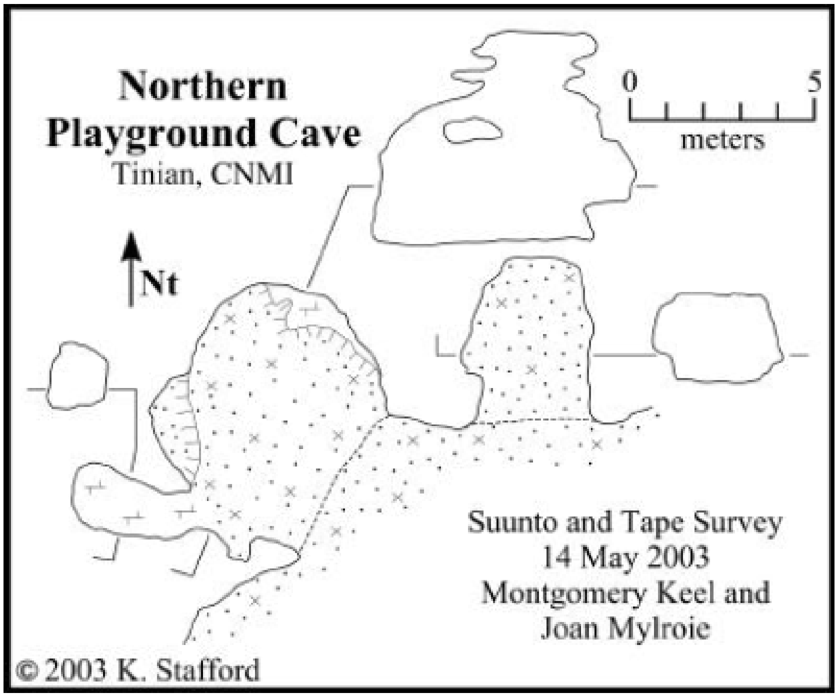

Figure 352: Map of Northern Playground Cave

Piña Cave Complex

Piña Cave Complex is located in the southeastern region of the Piña ridge and consists of three caves developed in the Mariana Limestone (QTmu). The larger cave is located at the southern end of this scarp segment and consists of three primary parts. The entrance area is 6 meters wide and extends inland, to the north for 5 meters forming the soil and detritus floored, entrance chamber. From the entrance chamber, a bedrock-floored passage extends 8 meters to the west as an upper level passage. To the south, a passage extends 4 meters and terminates in an elevated ledge. The two other caves are small and located 38 meters northeast of the larger cave. These two small caves are 3 meters apart with the western cave developed 2 meters high on the scarp and the eastern cave developed at the base of the scarp. Both caves extend inland 2 meters with ceiling heights less than 2 meters. The western cave exhibits a bedrock floor and the eastern cave has a soil, detritus, and breakdown floor.

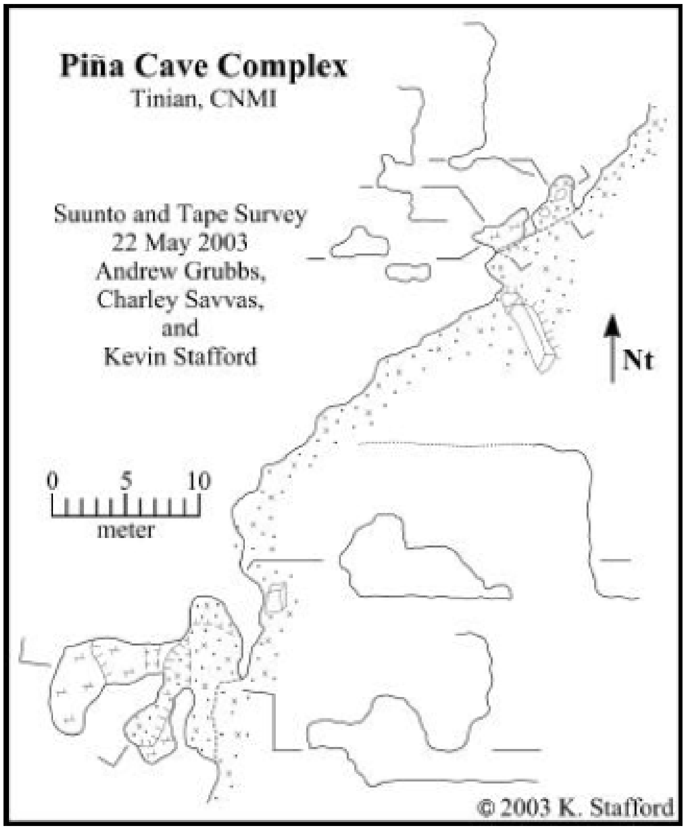

Figure 353: Map of Piña Cave Complex

Playground Cave

Playground Cave is located in the southeast region of the Piña ridge and is composed of two caves along a scarp segment that is developed in the Mariana Limestone (QTmu). The larger cave extends inland to the west with an entrance 13 meters wide and a 1-meter by 2-meter bedrock column located in southern part of the entrance. It reaches its largest dimension in the northern part of this cave, where it extends inland 7 meters with a ceiling height of 9 meters. A smaller passage, 2 meters wide, extends west from the larger cave for 4 meters. In this larger portion, a collapsed rock wall is present which indicates human modification of the feature, but the remainder of the cave has a soil and detritus floor. The smaller cave is 8 meters northeast of the larger cave and has two entrances separated by a 2-meter diameter bedrock column. The west entrance leads to a small passage that is 1 meter tall, while the east passage has a ceiling height of 7 meters and extends to the north, roughly parallel to the scarp face, for 4.5 meters, forming the majority of this smaller cave.

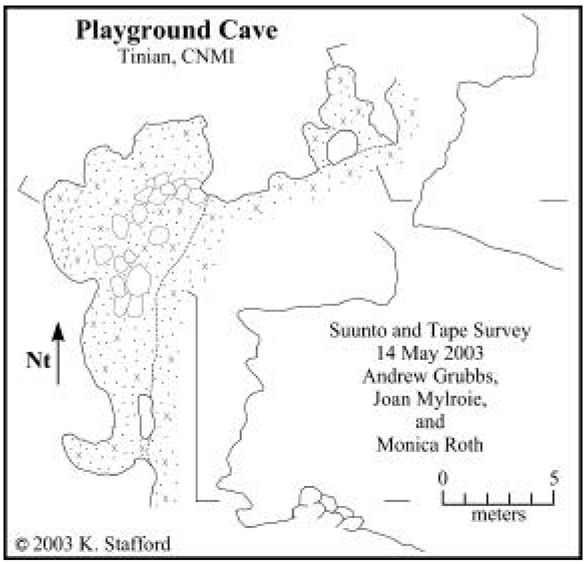

Figure 354: Map of Playground Cave

Radio Inactive Cave

Radio Inactive Cave is located in the central region of Suicide Cliffs in the Mariana Limestone (QTmu). It is a flank margin cave remnant that has been breached by scarp retreat with a 13-meter wide cliff entrance and a 2-meter diameter pit entrance in the inland part of the cave. The cave extends 21 meters inland with an average ceiling height of 3 meters, forming a chamber with an average width of 7 meters that is partially divided by three bedrock columns. The scarp entrance area has a bedrock floor with some speleothems, primarily has stalagmites and columns. In the inland areas, near the pit entrance, the cave has fewer speleothems and the floor is covered with alluvium. The cave has been slightly modified by humans with some leveling of alluvial floors and deteriorating wooden floors. The cave is named for a Japanese military radio that was found in the there.

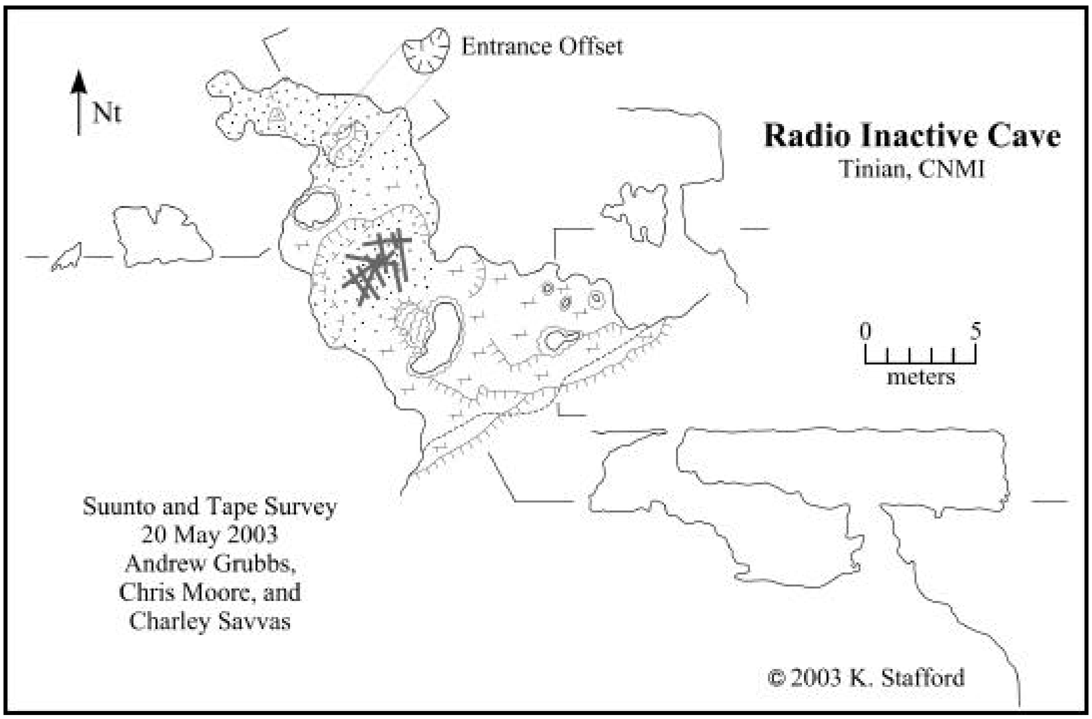

Figure 355: Map of Radio Inactive Cave

Skip Jack Cave

Skip Jack Cave is located 1500 meters northwest of *Puntan* Carolinas on the west coast at sea level. It is a breached, flank margin cave consisting of two primary chambers developed in the Mariana Limestone (QTmu). The entrance chamber is 18 meters wide and extends inland 14 meters, with a height above sea level of 8 meters and depth below sea level of 5 meters. Several small passages extend from this entrance chamber along fractures oriented north/south, while the second chamber extends inland 25 meters from the northeast corner of the entrance chamber. The second chamber ascends above sea level with an average width of 13 meters and height of 5 meters. The second chamber contains several large breakdown blocks covering a bedrock floor with a large mound of flowstone along the western edge of the chamber. This cave is not easily accessed from the surface, but requires a coastal swim from a small inlet located 400 meters north of the feature.

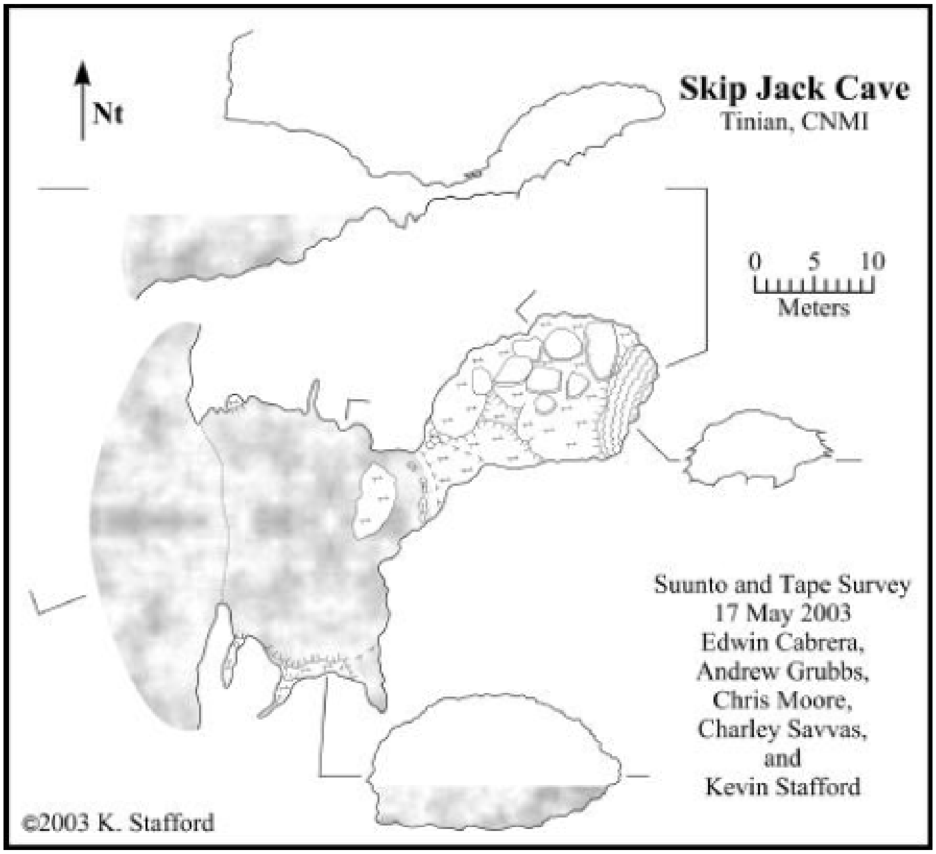

Figure 356: Map of Skip Jack Cave

Skull Cave Complex

Skull Cave Complex is located in the southeastern region of the Piña ridge in the Mariana Limestone (QTmu). It consists of three flank margin cave remnants that extend inland to the west. The southern cave in the complex is located 2.5 meters high on the scarp and extends inland 3 meters with a bedrock floor with a ceiling height of 1.5 meters and an entrance width of 8 meters. The middle cave in the complex is 1.5 meters wide at the entrance, then widens to 8 meters and extends inland 5 meters. This middle cave has a large breakdown block, partially concealing the 1-meter tall entrance, which then increasing to 2.5 meters tall with a soil and detritus floor and a small bedrock ledge in the southwest corner. The largest cave is located at the northern edge of the complex and consists of soil and detritus floored chamber that extends inland 10 meters with an average width of 8 meters. The entrance area consists of three breached entrances; two at ground level and one 2 meters above the ground surface. This cave is named for the skull-like appearance of the three entrances. The entire complex shows minor human modification primarily in the form of leveled floors.

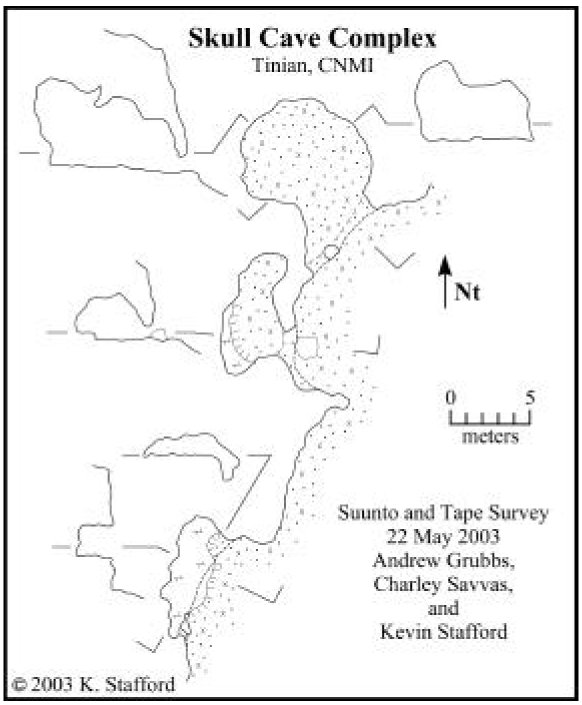

Figure 357: Map of Skull Cave Complex

Skylight Cave

Skylight Cave is located in the central region of Suicide Cliffs in the Mariana Limestone (QTmu). The cave is located 5 meters below the top of the cliff with a cliffside entrance that is 9 meters wide and 2 meters tall. The cave extends inland 12 meters with and average width of 4 meters before it is breached on the inland side by ceiling collapse. The cave contains several speleothem columns as well as a large flowstone mound along the eastern side. The inland part contains several large breakdown blocks and a soil and detritus floor, while the regions near the cliff edge contain a bedrock floor. The feature is primarily a linear passage extending inland to the north, with several small solutional pockets that extend east and west of the main cave.

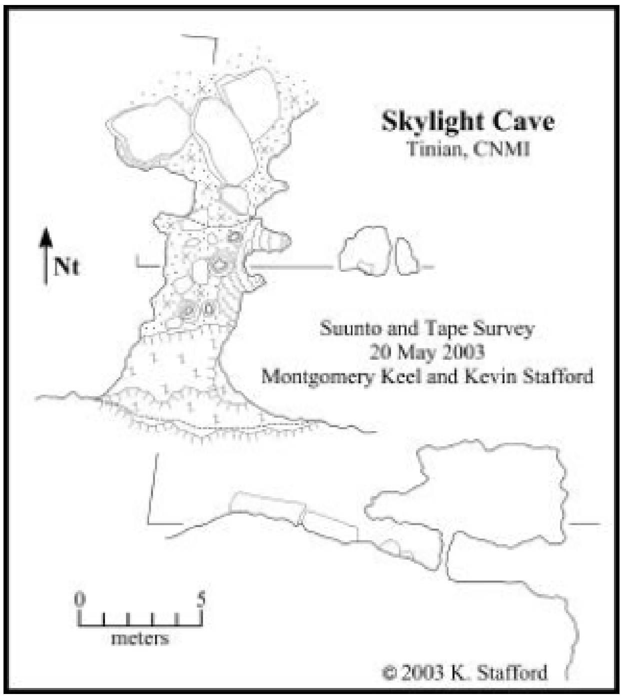

Figure 358: Map of Skylight Cave

Solitary Cave

Solitary Cave is located 1500 meters south of *Unai Masalok*, is the only cave that has been identified on the western scarp of Piña ridge. This small, flank margin cave remnant is developed in the Mariana Limestone (QTmu). The cave has and entrance 2 meters wide, extends inland 2 meters and widens to 3 meters with a ceiling height of 1.5 meters. The cave appears to have been extensively modified, including some enlargement of the cave and the construction of a rock wall 2.5 meters long and 1 meter tall, which conceals the majority of the entrance. This feature was not surveyed at the time of discovery, because it was the only feature located during the exploration of this region and a survey crew did not return to the region in order to survey this small, solitary feature.

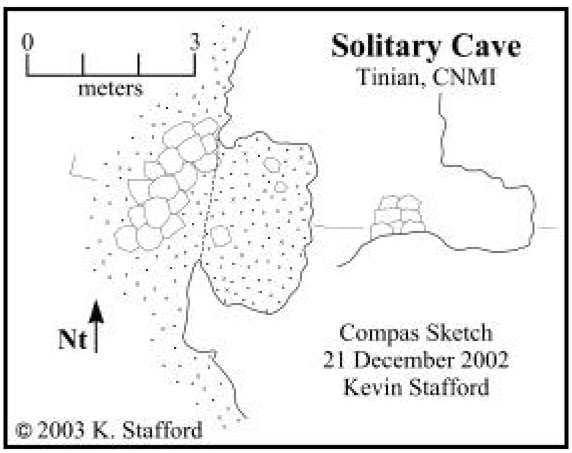

Figure 359: Map of Solitary Cave

Twin Ascent Caves

These two caves are located in the central part of Suicide Cliffs, approximately 25 meters above the base of the cliff. They are the remnants of a breached flank margin cave developed in the *Tagpochau* Limestone (Tt) and are connected by a small, roofed ledge approximately 0.5 meters tall, indicating that the two features were joined as one cave prior to cliff retreat. The larger of the features is 11 meters by 15 meters with a maximum ceiling height of 9 meters, while the smaller feature is 8 meters by 10 meters with a similar ceiling height. In both caves, speleothems are present and in the larger feature minor excavation of the floor indicates that the feature was modified for use during WWII.

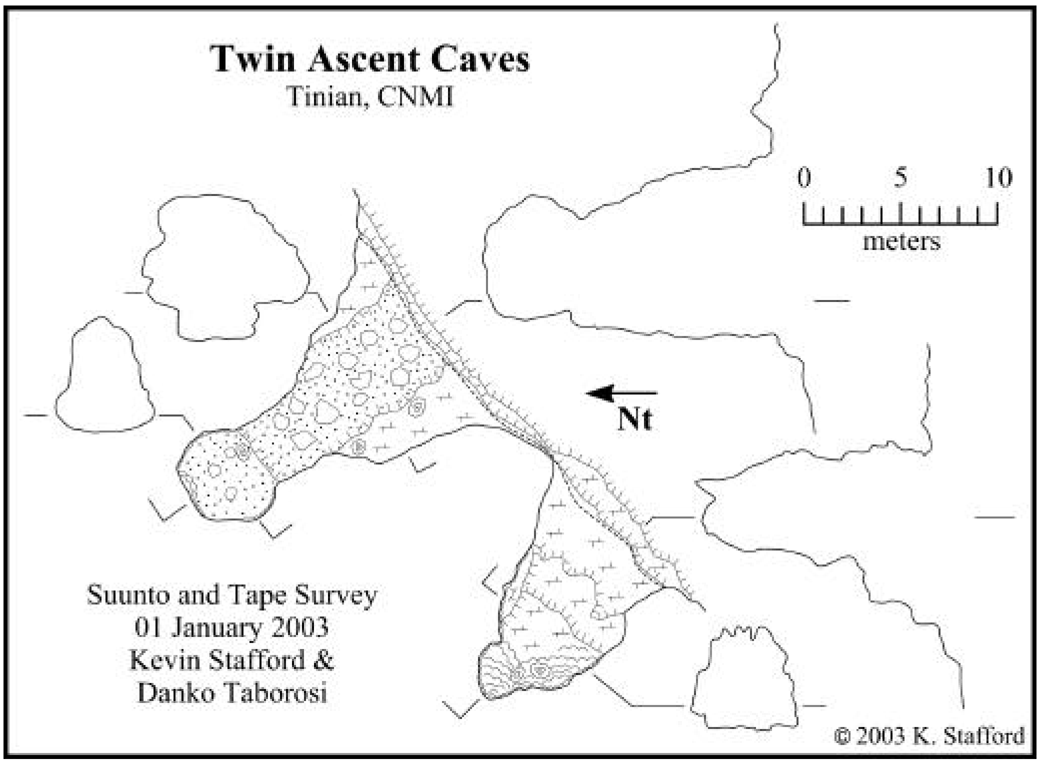

Figure 360: Map of Twin Ascent Caves

West Suicide Cliff Caves

West Suicide Cliff Caves, developed in the Mariana Limestone (QTmu), are located at the west end of Suicide Cliffs near Carolina's Limestone Forest. This series of caves is located near the base of the cliff and represent a series of features breached by cliff retreat. The two caves on the southeastern portion of the series are approximately 18 meters by 6 meters each with ceiling heights ranging from 3 to 6 meters. They exhibit few speleothems and have extensive alluvium deposits on their floors. The largest, center cave, in this series is approximately 10 meters by 14 meters with a ceiling height of 6 meters. Associated with the center cave are two small cave remnants above the main chamber and a third small cave beneath it. West of the central cave are three small caves that do not extend inland a significant distance and a fourth larger remnant cave that is approximately 70 meters to the northwest of the central cave. The remnant cave that is the farthest to the west is approximately 8 meters by 10 meters with little ceiling remaining because of cliff retreat.

It is not possible to tell if these features were originally connected prior to cliff retreat, but it is thought that at least some of the features were joined in the past, because they are developed along a consistent horizon and are closely spaced, especially in the central and southeastern portions of this series.

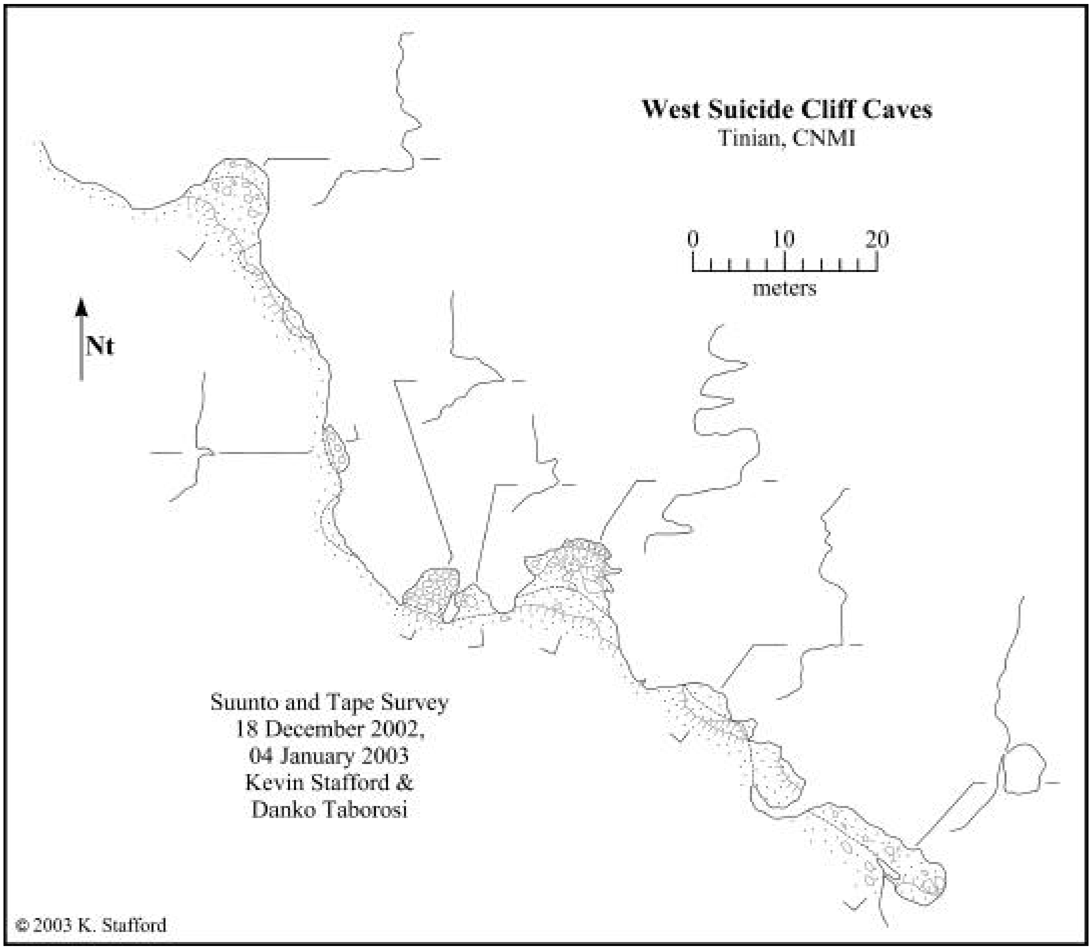

Figure 361: Map of West Suicide Cliff Cave Complex

Mixing-Zone Fracture Caves

"600 Meter" Fracture System

The "600 Meter" Fracture System is a high-angle fracture located approximately 500 meters west/northwest of *Puntan Masalok* in the Mariana Limestone (QTmu), where it trends northwest (~310°) for over 300 meters before the feature becomes obscured by additional surface features and vegetation, however topographic maps for the island confirm that it extends for approximately 600 meters (United States

Department of the Interior Geological Survey, 1983). Full Bottle Cave is located in the northwest portion of the fracture system, while *Masalok* Fracture Cave is located in the southeast portion. Numerous small pocket caves are located in the northeastern scarp wall along the entire length of the feature, however fewer are present in the regions where a southwestern wall is present. Throughout the feature, numerous speleothems are present on the cliff walls and within the small pocket caves, indicating that at some point in the past this feature was roofed. In the middle portions of the feature, where two cliff walls are exposed at the surface, the feature measures over 5 meters wide with a northeastern wall that is approximately 10 meters tall and a southwestern wall that is approximately 3 meters tall. Along the fracture, several less dissolutionally enhanced fractures are intersected at high angles to the primary fracture. In addition, several small collapse areas in the breakdown floor are present, indicating that greater void space is present at depth. This extensive, dissolutionally enhanced fracture system demonstrates the importance of fractures within carbonate islands as routes for the transfer of water into the subsurface.

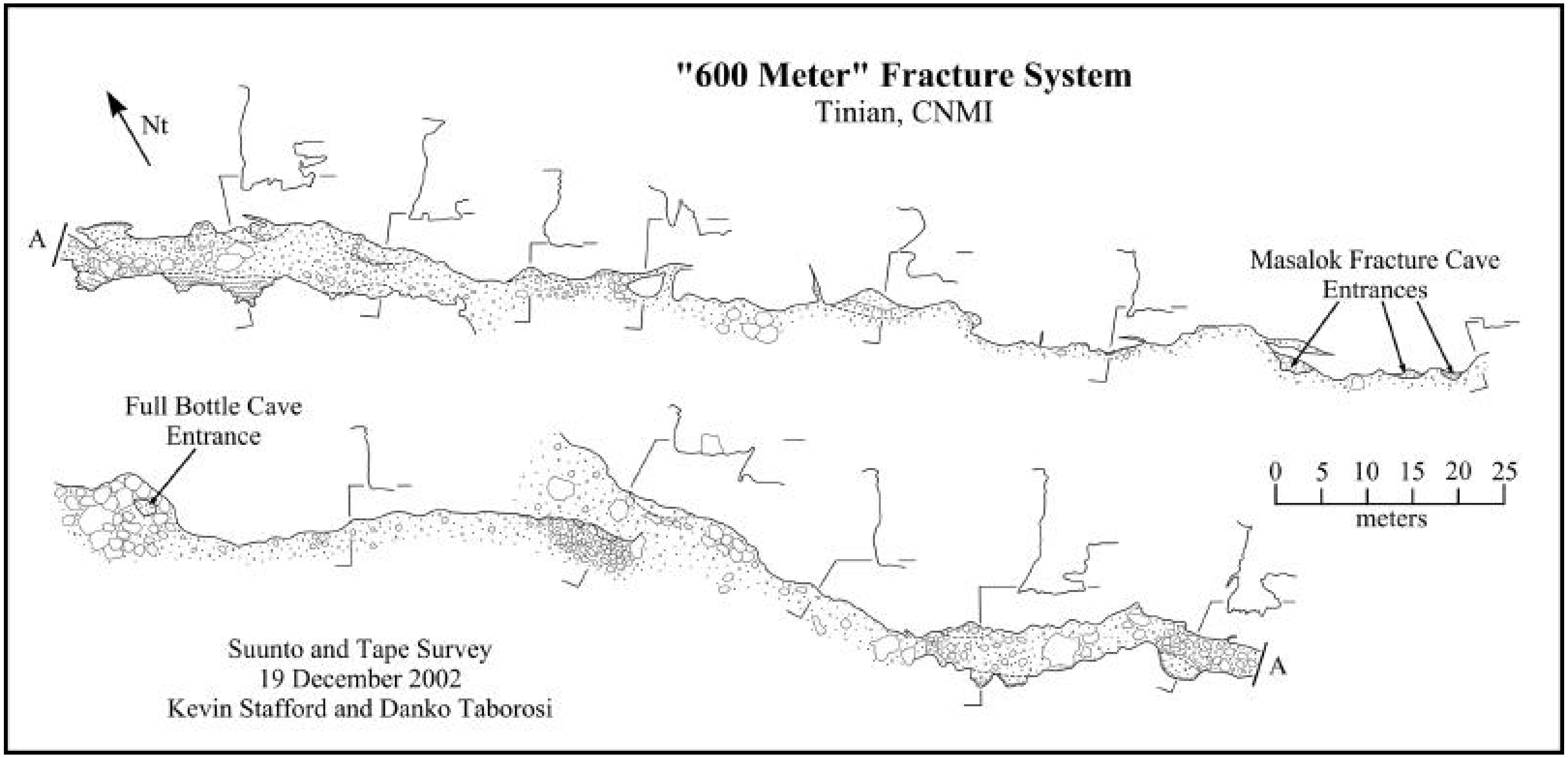

Figure 362: Map of "600 Meter" Fracture System.

Pit Caves

Headless Tourist Pit

Headless Tourist Pit, developed in the Mariana Limestone (QTmu), is located approximately 500 meters east of *Puntan* Carolinas, 6 meters from the coastal cliff. The feature is on the coastal terrace, which has extensive phytokarst development. It is approximately 3 by 5 meters in diameter at the entrance and narrows to 0.5 by 3 meters at a depth of 10 meters, before widening into a joint controlled collapse chamber, which forms a littoral cave that connects to the ocean approximately 5 meters above the coastal bioerosion notch. The upper portions of the pit exhibit phytokarst development and collapse, while the restricted middle region contains minor secondary deposits. The lower chamber, which connects to the ocean, is approximately 8 meters wide and 15 meters long, with joints extending to the northeast and northwest. This feature is evidence of pit formation acting as vadose fast flow routes on the island of Tinian. Although it does not provide fast flow recharge to the aquifer, because of its direct connection to the ocean, it does demonstrate the presence of pits on Tinian.

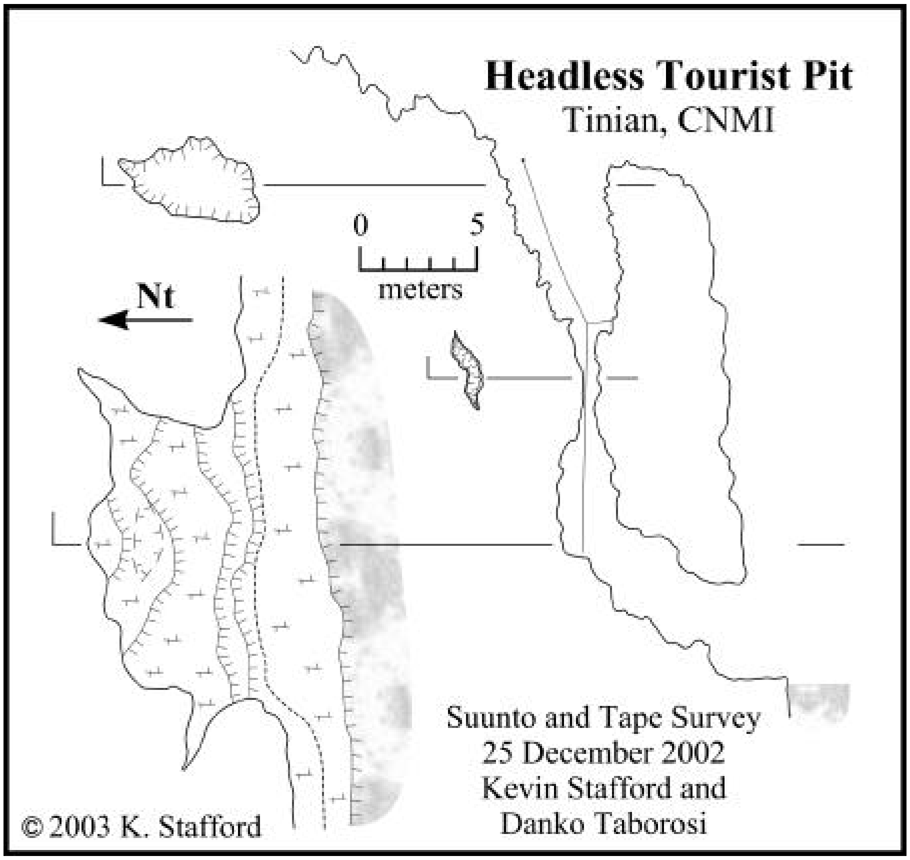

Figure 363: Map of Headless Tourist Pit